Direct Detection of Dark Matter

Graciela Gelmini - UCLA

LNGS, October 21, 2014

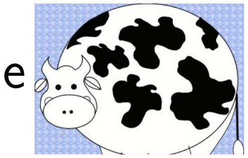
Content of Lecture 2

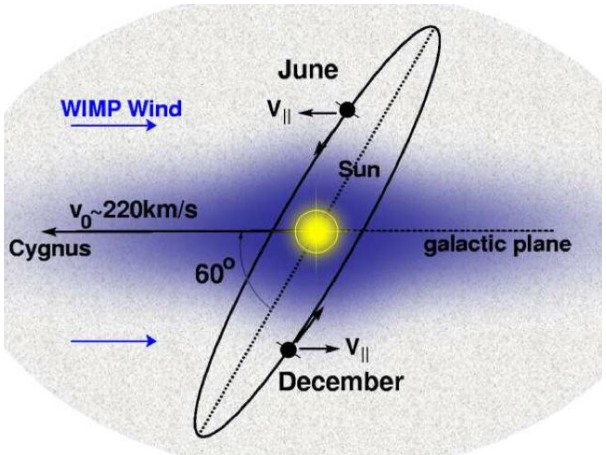
- Uncertainties in the models of the dark halo of our galaxy
- Halo-dependent direct detection data analysis

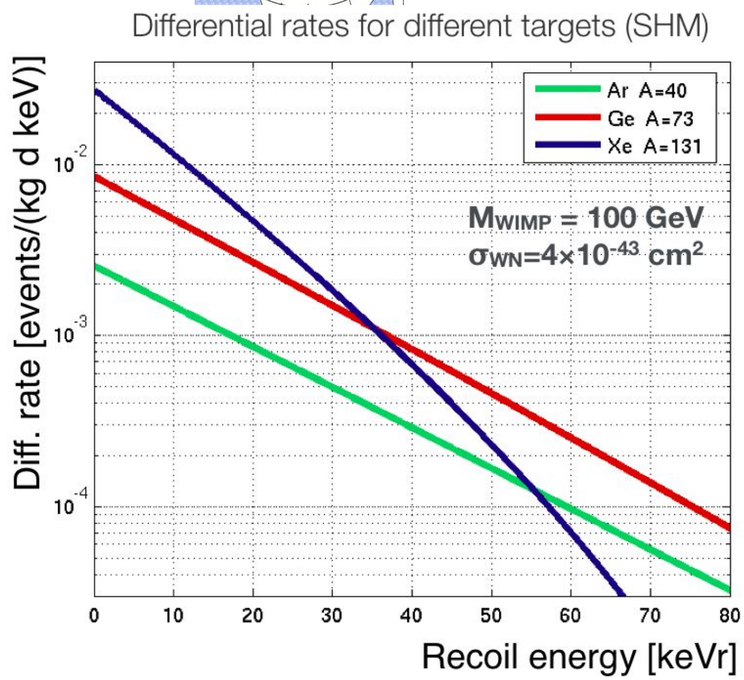
Elements of the Event Rate

[Event Rate] = [Detector Response] x [Cross Section] x [Halo Model]

How many dark matter particles are passing through the detector and with which velocity distribution?

Standard Halo Model (SHM) The  of halo models





- $\rho_{SHM} = 0.3^{+0.2}_{-0.1}$ GeV/cm^3
- $f(v,t)$: Maxwellian $\vec{v}$ distribution

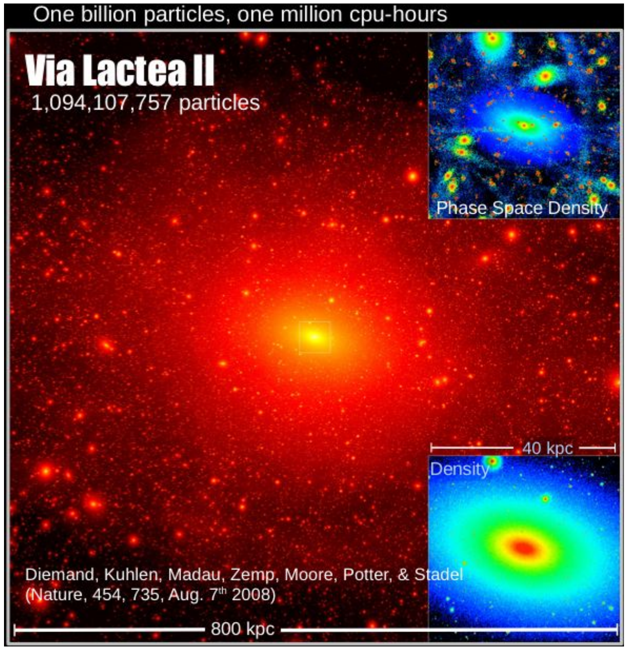
at rest with the Galaxy $v_\odot \simeq$220km/s (190 to 320km/s), $v_{esc} \simeq$530-650km/s

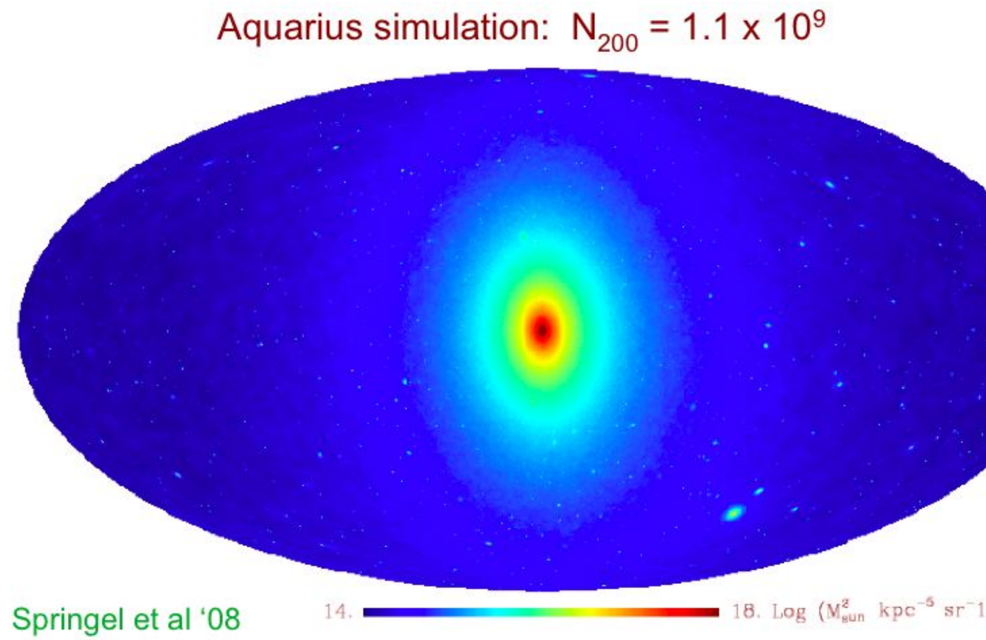
ANNUAL MODULATION: max in May, min in Dec.(Drukier, Freese, Spergel 1986)

Local ρ, v, modulation phase/amplitude could be very different if Earth is within a DM clump or stream or there is a "Dark Disk". Other: anisotropies, velocity tails, debris flows...

State of the art non-linear N-body simulations of Dark Haloes

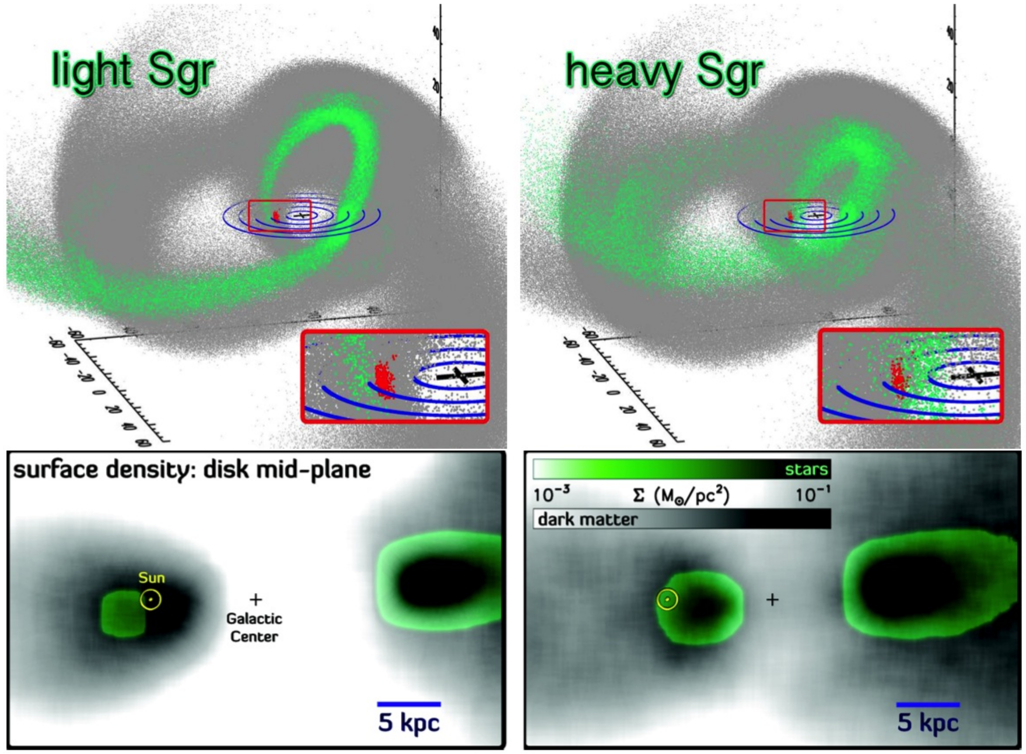
No baryons included (so no disk)! Sun at 8kpc from the center





Lots of subhalos and tidal streams at large distances from the galactic center. The chance of a random point close to the Sun lying in a substructure is $< 10^{-4}$, but the SGR leading trail could and "debris flows" do pass by the Sun

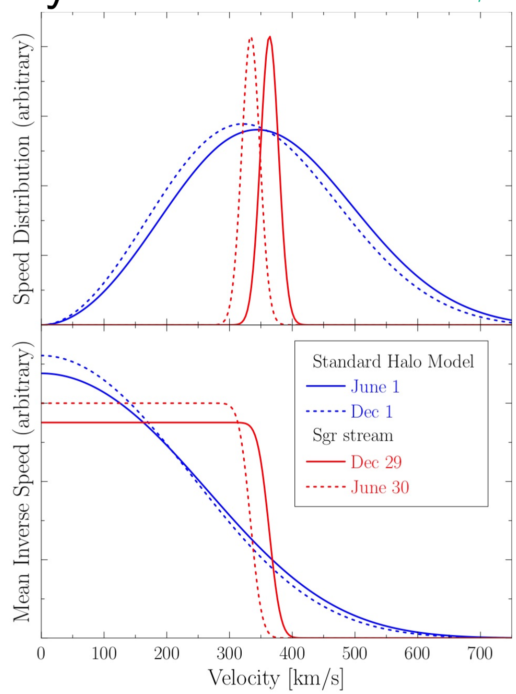
Sgr. leading trail DM passing through the Solar System



Large uncertainties in local stream density, $\rho_{Sgr} < 5\%\ \rho_{SHM}$ and velocity, $v \simeq 250 - 400$ km/s with respect to the Sun Purcell, Zentner, Wang 1203.6617

SHM + DM in the Sgr. leading trail

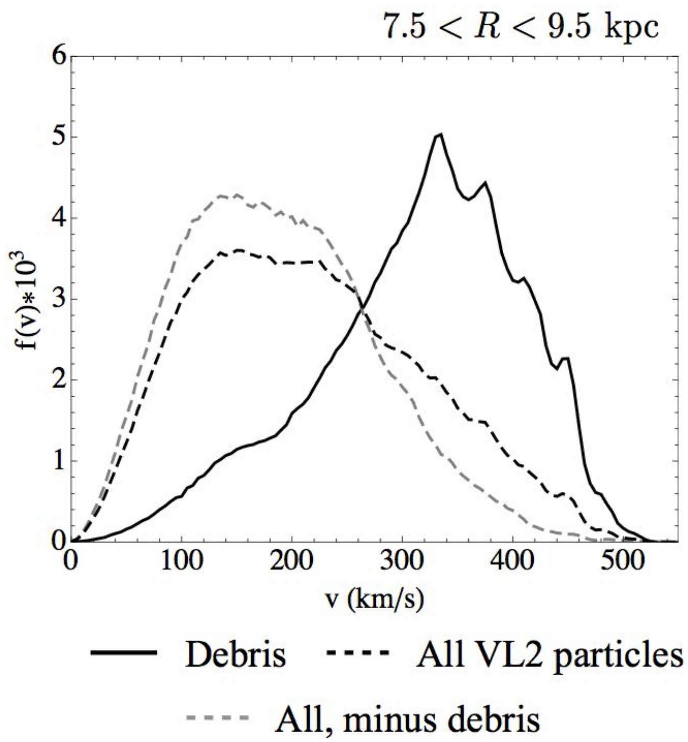
Schematic speed distribution and integral $\eta(v)$ with arbitrary normalization Freese, Lisanti & Savage 1209.3339

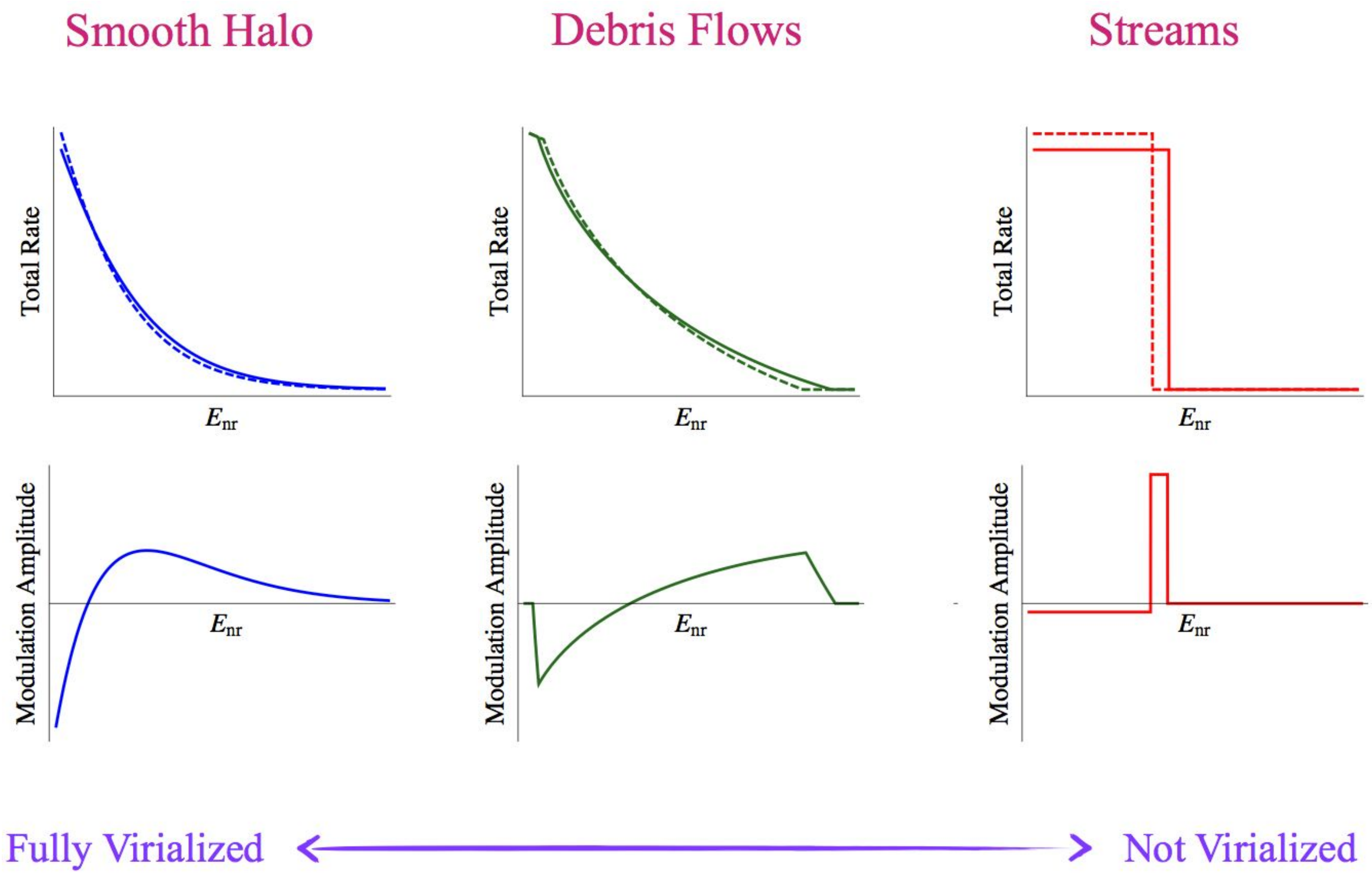


For $m_\chi < 20$ GeV, Sgr DM stream could enhance Direct DM detection rate by by 20% to 45%, reduce the annual modulation amplitude by as much as 50% and change its phase by 20 days (but large uncertainties) Purcell, Zentner, Wang 1203.6617

"Debris Flows" Lisanti & Spergel 2011, Khulen, Lisanti & Spergel 2012

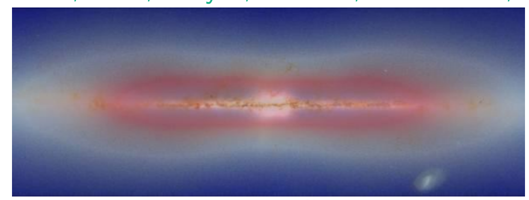
Spatially homogeneous, structures in velocity





Freese, Lisanti & Savage 1209.3339

Dark Disk: Read, Lake, Agertz, Debattista MNRA 389, 8/2008;Read, Mayer, Brooks, Governato, Lake 0902.0009



Read et al **include baryons in simulations with CDM**: "A stellar/gas disc, already in place at high redshift, causes merging satellites to be dragged preferentially towards the disc plane where they are torn apart by tides."

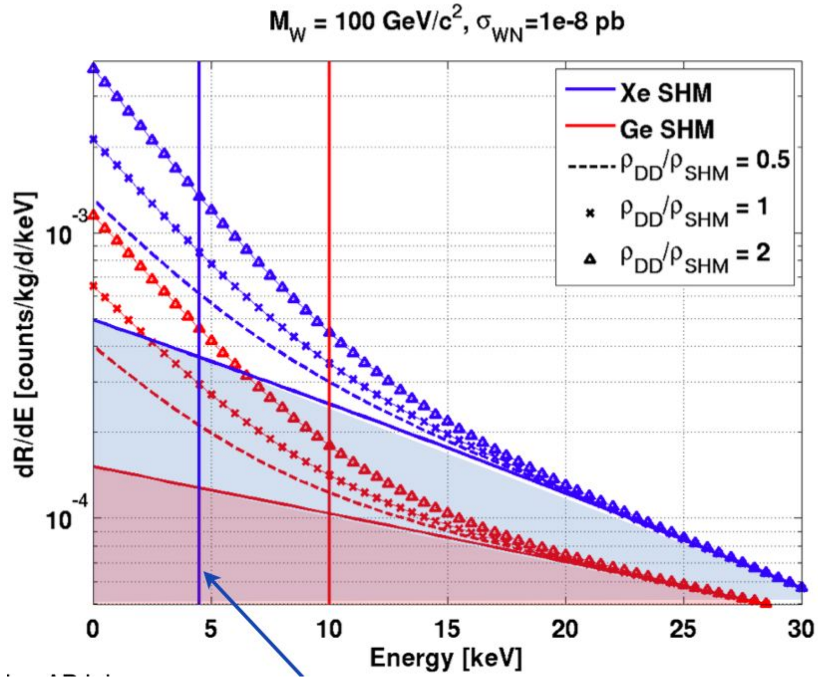
Dark Disk: equilibrium structure

$\rho_D \leq 2 \times \rho_{SHM}$

$v_{lag} \simeq 50$ km/s with respect to Sun

$v_{disp} \simeq 50$ km/s

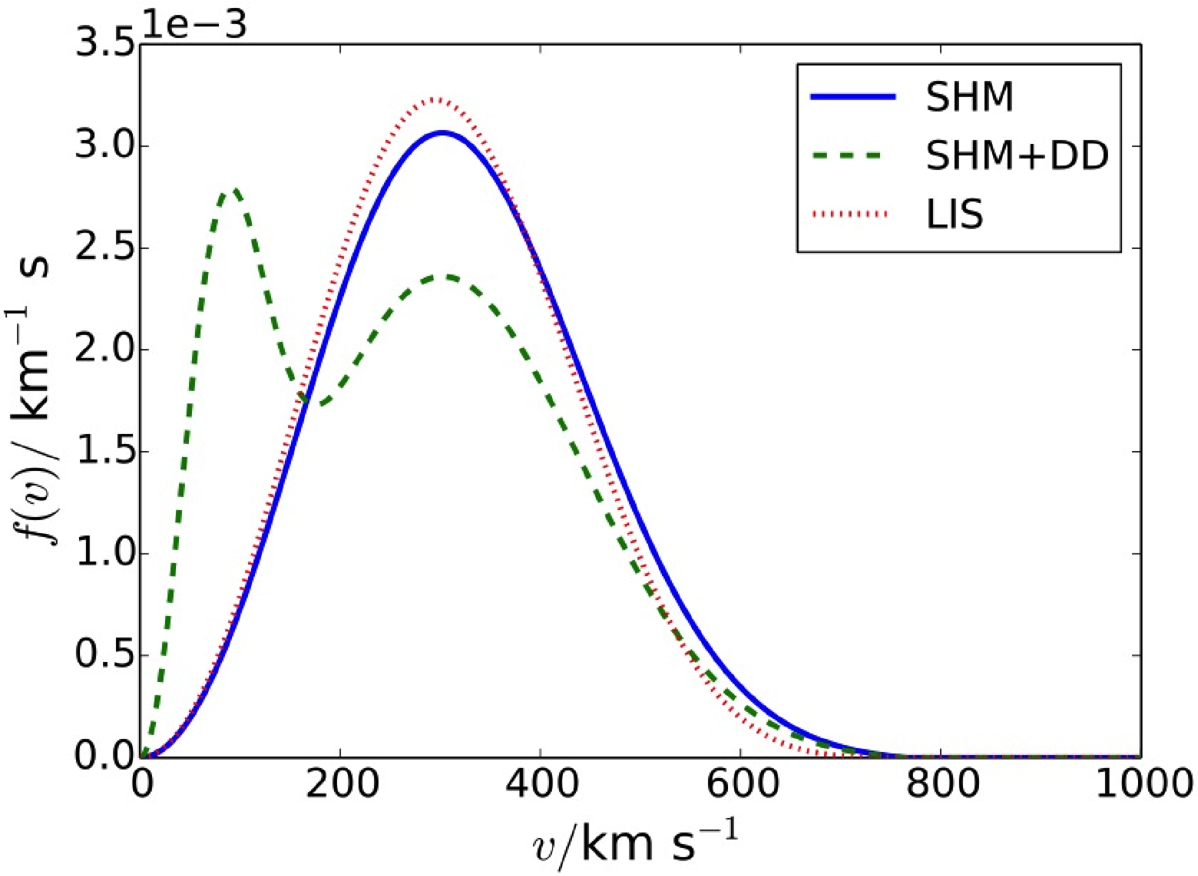
Very rare feature with simple CDM but pervasive if part of the DM is dissipative, as in DDDM Fan, Katz, Randall & Reece 1303.1521-1303.3271



Threshold of XENON 10

Bruch, Read, Baudis, Lake Ap.J.696:920-923,2009 and arXiv:0811.4172

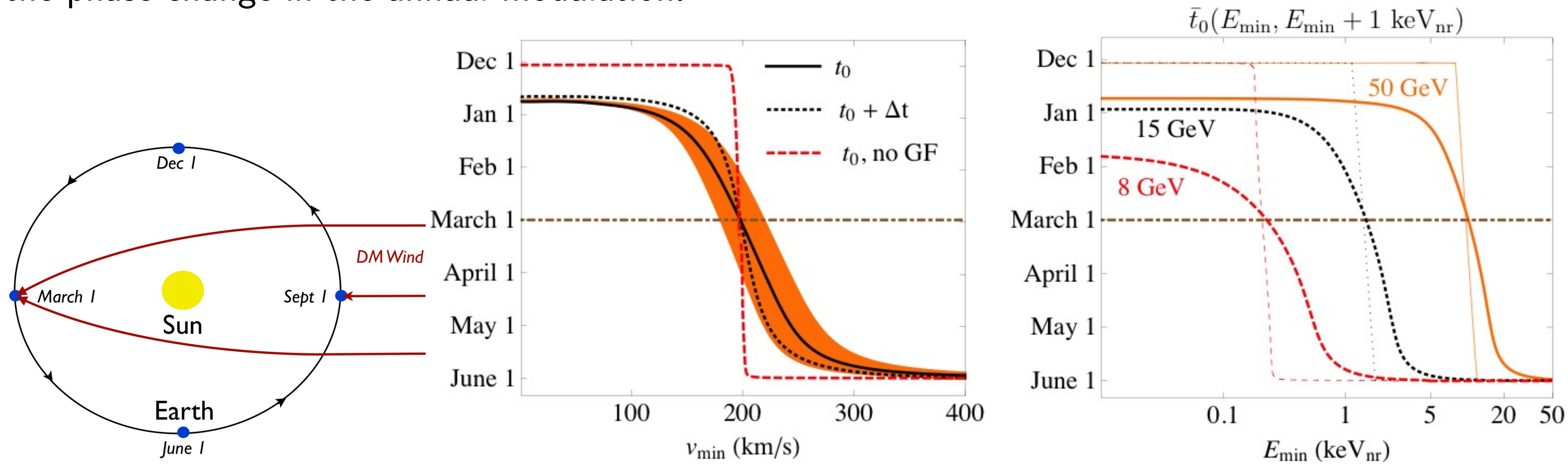
Dark Disk enhanced population at very low speeds



Peter, Gluscevic, Green, Kavanah & Lee 1310.7039

Gravitational Focussing by the Sun affects the Annual Modulation for low velocity WIMPs Lee, Lisanti, Peter & Safdi 1308.1953

GF effect computed by Alenazi & Gondolo in 2006, 0608390, but Lee et. al pointed out in 2013 the phase change in the annual modulation.



t_0: date of the halo integral $\eta(v_{min}, t)$. Right Plot: for elastic scattering in Ge

Effect only visible with very low energy threshold! The DAMA/LIBRA fits change very little due to this effect Bozorgnia & Schwetz 1405.2340

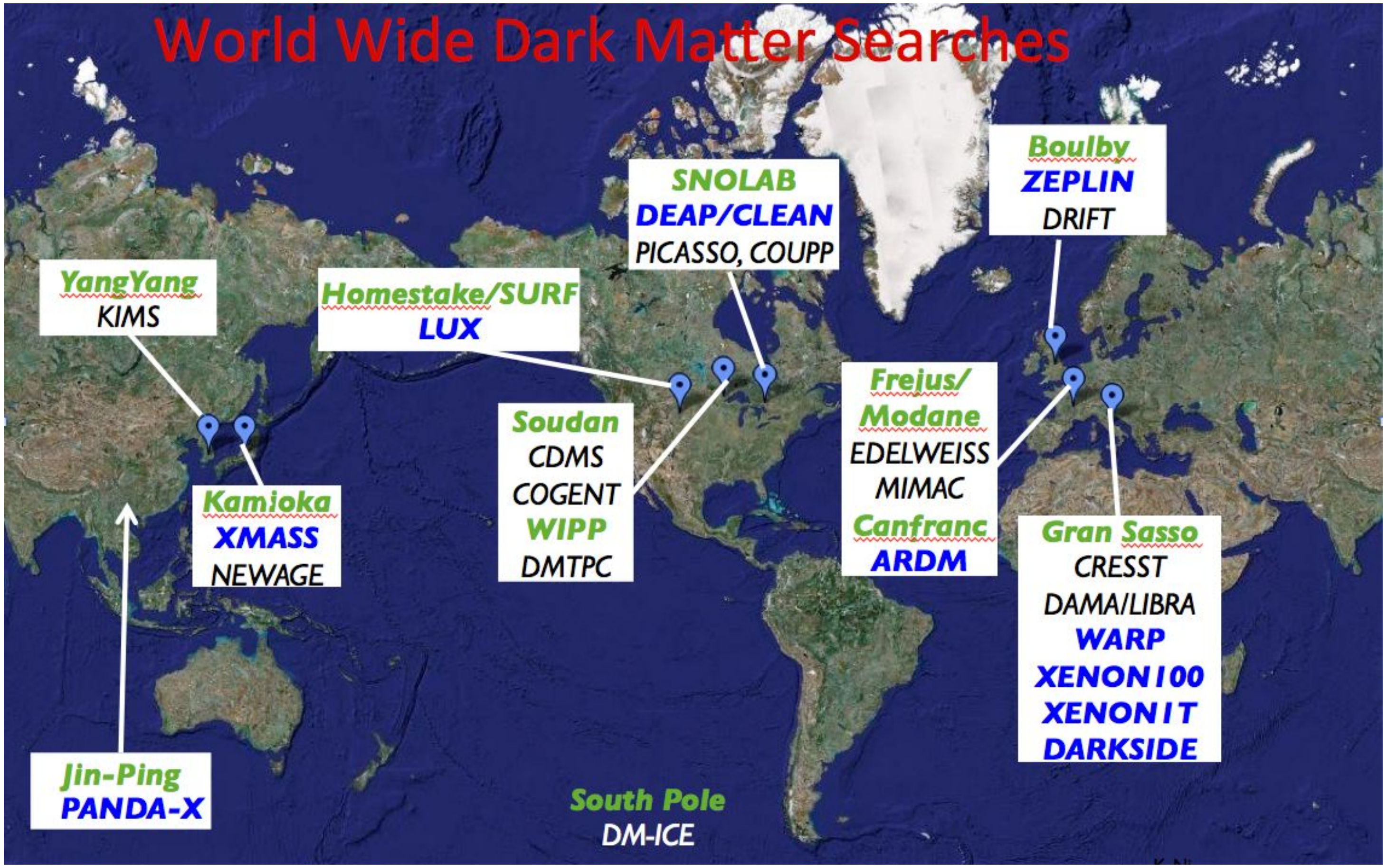
Synopsis of the lectures so far

- We do not know if the dark matter consists of particles, and if it does, which the masses and the interactions (if any besides gravitational) of these particles are. We must keep a very open mind with respect to DM particle properties and models avoiding oversimplications.

- DM particles require new physics beyond the SM! But this new physics may or may not be related to the electroweak hierarchy problem. In recent years plenty of DM particle models have been proposed to account for desired DM properties (entire dark sectors, strong self interactions, partially dissipative, with inelastic collisions.....).

- The expected DM direct detection rate depends on: the detector response, the particle physics model of the DM, and the astrophysical modeling of the local properties of the Dark Halo of our galaxy and all have large uncertainties.

Direct DM Searches: Many experiments!



WIMP Direct DM searches:

DAMA (NaI), CoGeNT (Ge), CRESST II ($CaWO_4$) AND CDMS (Si) made potential detection claims....

Are they DM signals or backgrounds?

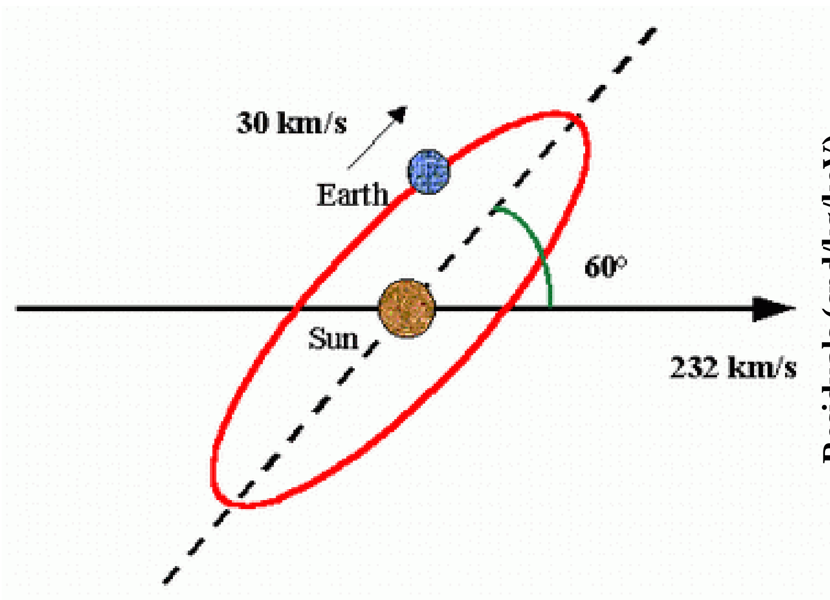
LUX (Xe) XENON 100 (Xe), XENON 10 (Xe), CDMS (Ge, Si), SuperCDMS (Ge), CDMSlite (Ge), SIMPLE (C_2ClF_5).... have upper bounds...

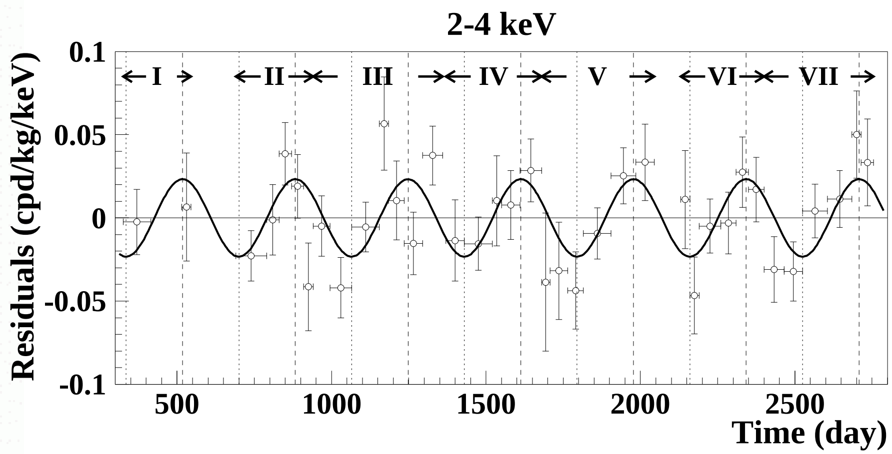
Assuming they are DM signals, can all signals and bounds be reconciled? Some of them?

Subject is too vast for the time- so idiosyncratic choice of subjects. Citations disclaimer

Let us review the DM signals: DAMA, CoGeNT, CRESST II, CDMS

Old DAMA/NaI: DM signal?



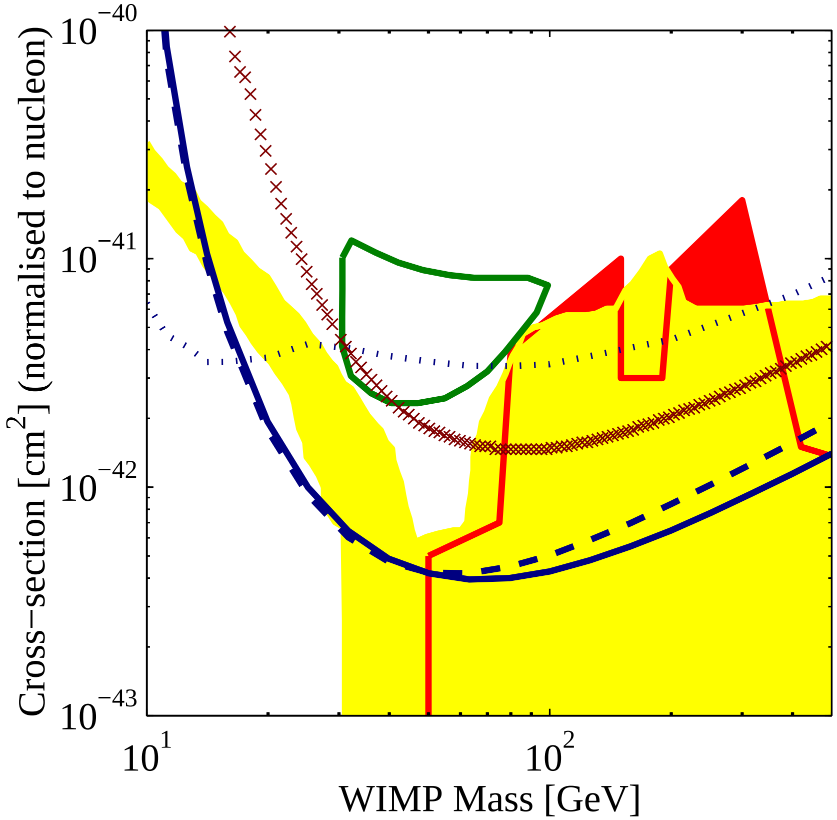


By 2002: 7 years of DAMA/NaI showed a 6σ modulation signal compatible with the Standard Halo Model.

Old DAMA/NaI SI WIMPs?

Theoretical prejudice:
DAMA region cut at m= 25 GeV
(from 1997 until 2003)
was excluded in 2002 by Edelweiss
(brown crosses) and in 2004 by
CDMS-Soudan (blue).

Theoretical Prejudice:
limits were never shown below
m=10 GeV either!



Bottino et al. light neutralinos m >6 GeV
Baltz et al.

Old DAMA SI WIMPs? Region compatible with all data!

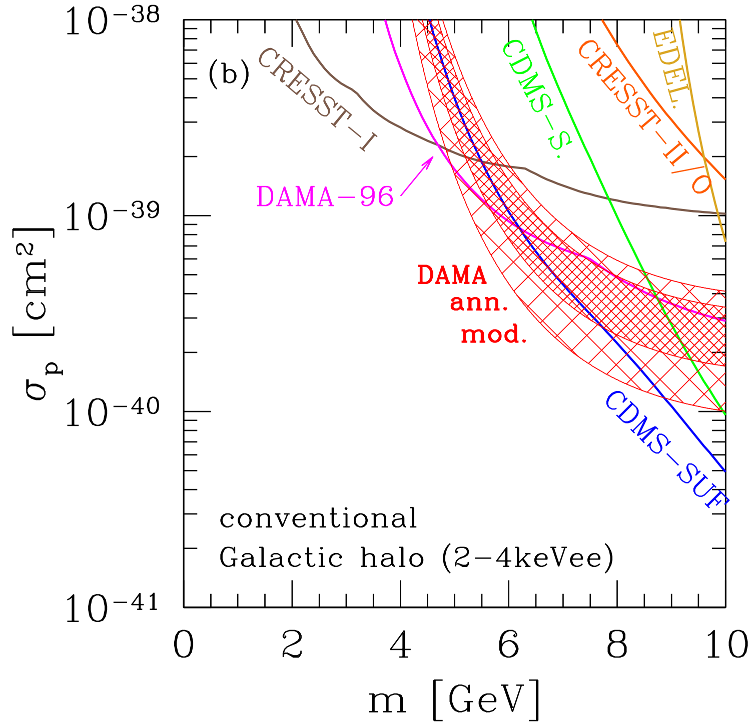
"DAMA dark matter detection compatible with other searches," Gelmini, Gondolo hep-ph/0405278; Gondolo Gelmini hep-ph/0504010

"Los muertos que vos matais gozan de buena salud" Gelmini, TAUP2005, Zaragoza

The bounds had never been extended to m< 10 GeV before.

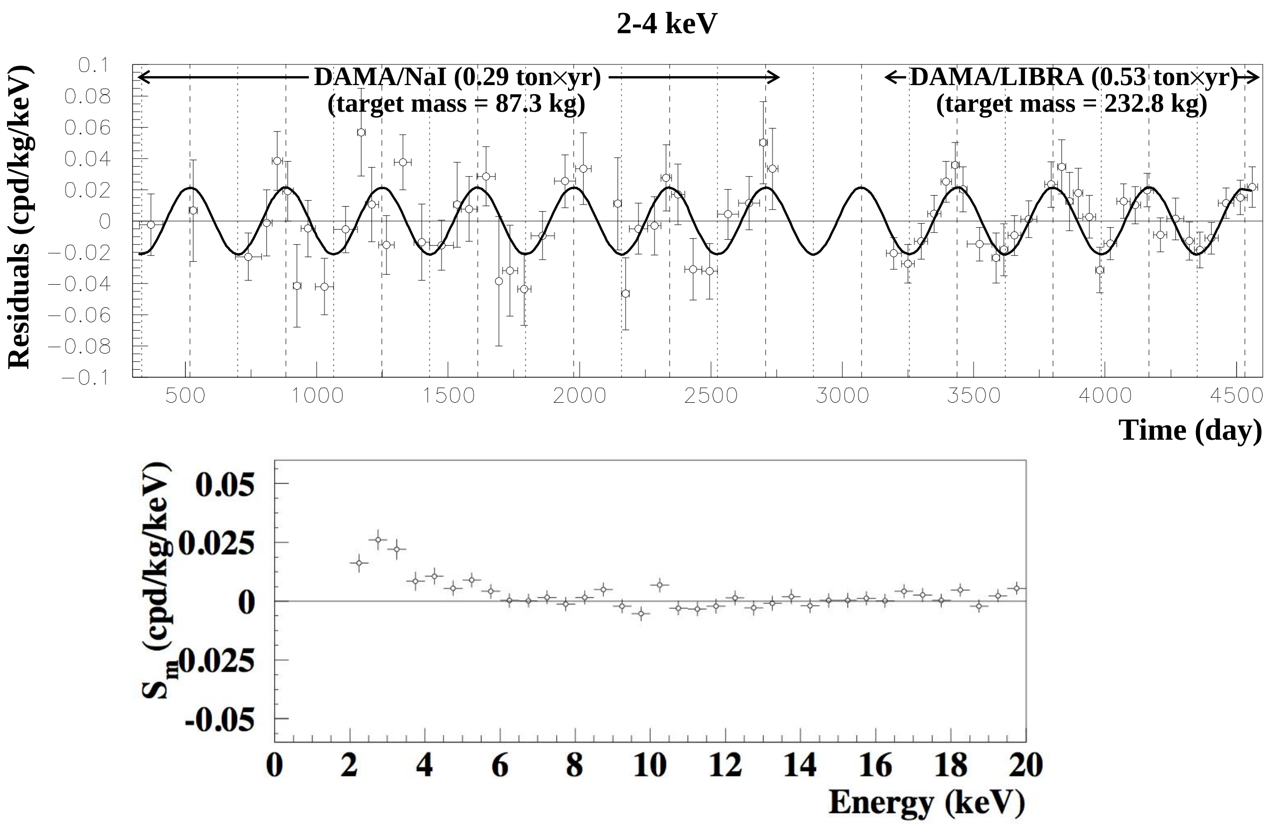
Due to its Na, DAMA could see a signal that was under threshold for Ge in CDMS and EDELWEISS

"Light WIMPs" region



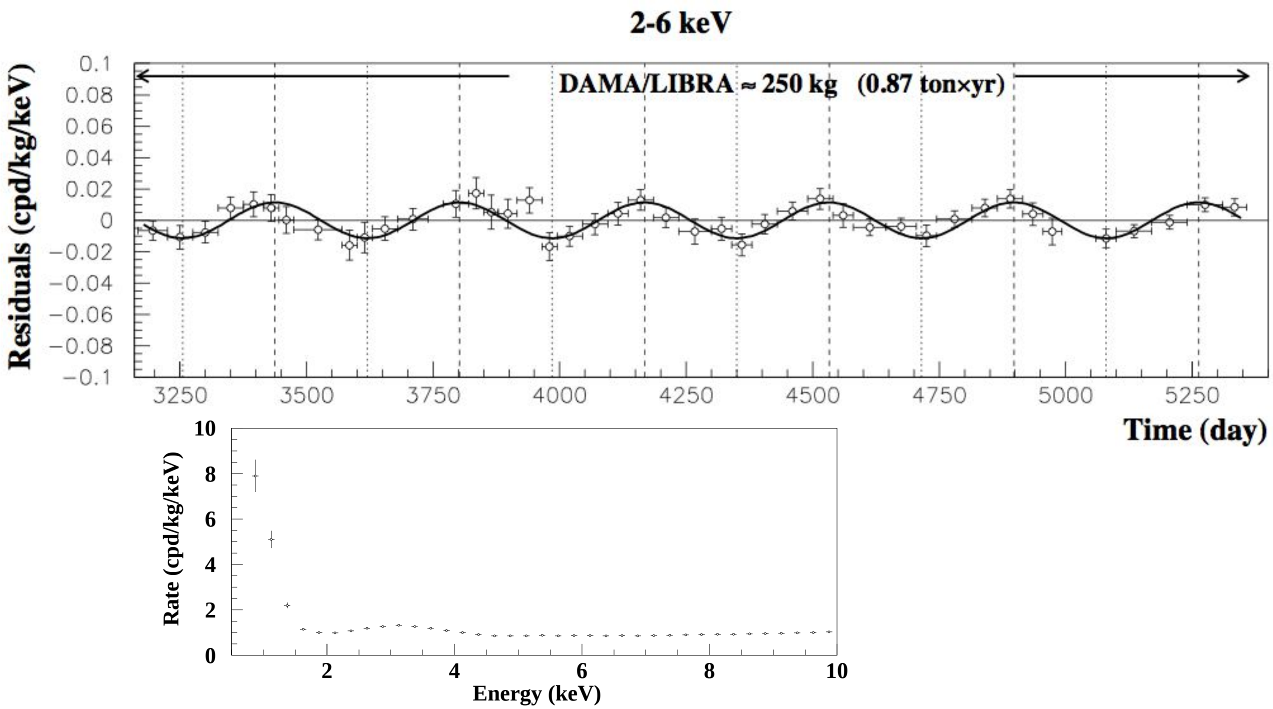
2008 DAMA/LIBRA

25 NaI (TI) crystals of 9.5 kg each, 4y in LIBRA (11 years total),
0.83 ton × year, 8.2σ modulation signal (Gran Sasso) (Bernabei et al 0804.2741)



2010 DAMA/LIBRA

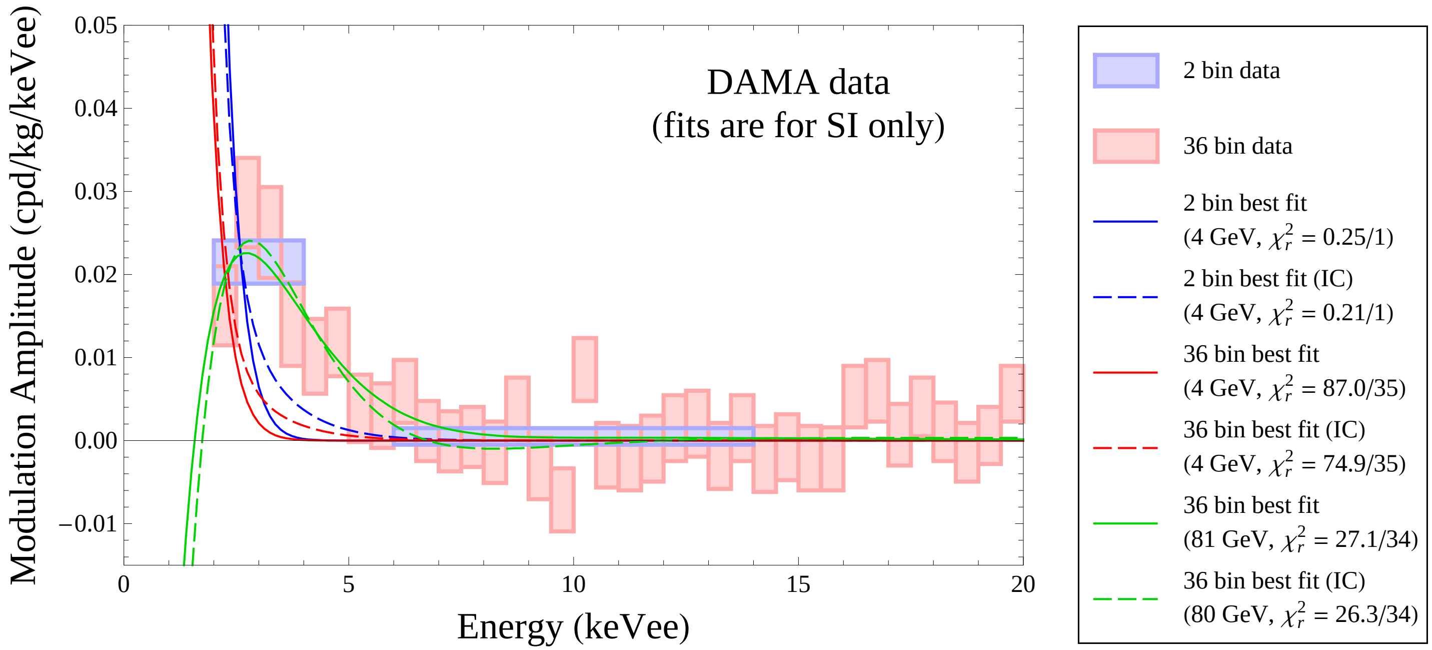
25 NaI (Tl) crystals of 9.5 kg each, 6y in LIBRA (13 years total), 1.17 ton × year, 8.9σ modulation signal.(Bernabei et al 1002.1028)



2013 DAMA/LIBRA 1.33 ton × year, 9.3σ modulation signal!

2008 DAMA/LIBRA modulation amplitude in 36 bins

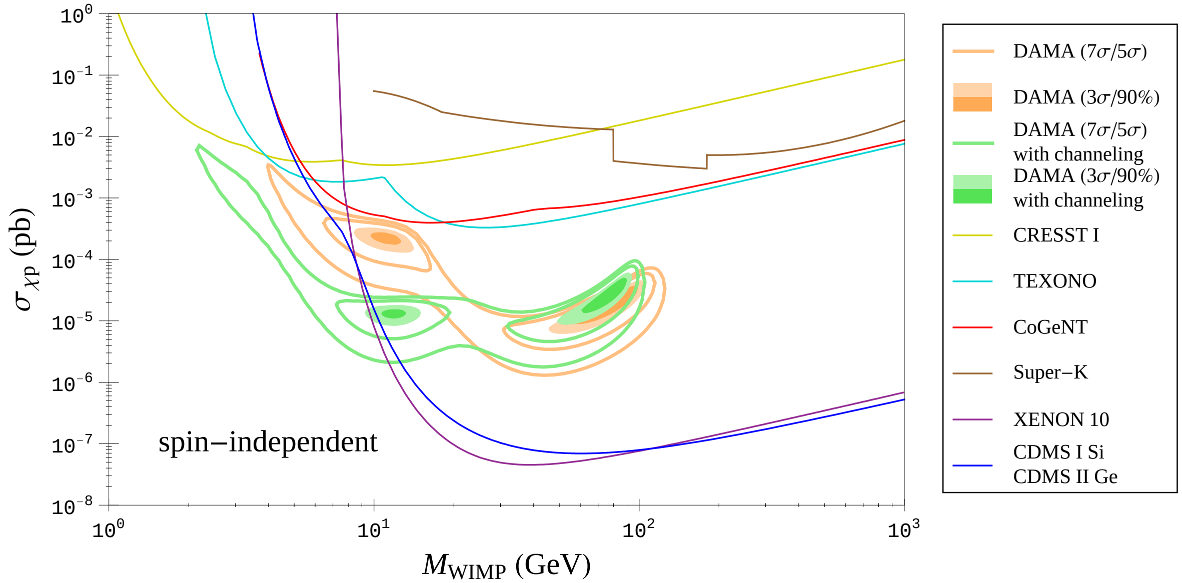
Savage,Gelmini, Gondolo and Freese 0808.3607



NOTICE: 1st bin lower than 2nd/3rd implies that HEAVY WIMPs (e.g.m =81 GeV)fit data better than LIGHT WIMPs (e.g.m =4GeV) Now taking 5y of data with lower threshold !

Upper limits: CoGeNT, CRESST, CDMS, XENON10, TEXONO...

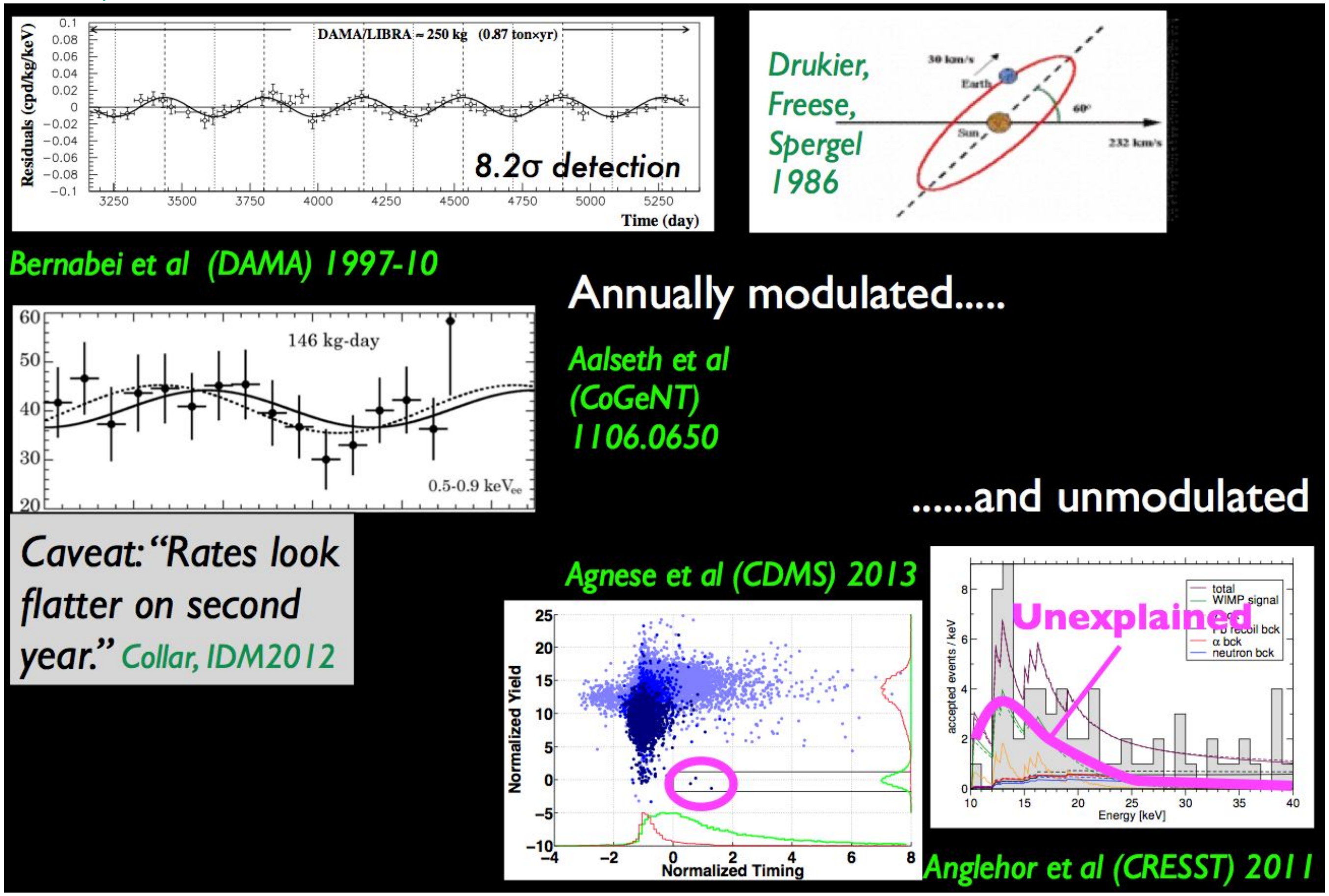
Savage, Gelmini, Gondolo and Freese, 0808.3607, JCAP 0904:010,2009



With the channeling fractions DAMA estimated in 2008 two distinct regions of light WIMPS $m \simeq$ 7-10 GeV with Na or channeled I recoils were a possible explanation- In 2010 understood that channeling is so small that is irrelevant for Direct Searches (Bozorgnia,GG. Gondolo 2010, Collar 2013 , KIMS)

2010-2013 DM hints in four direct detection experiments

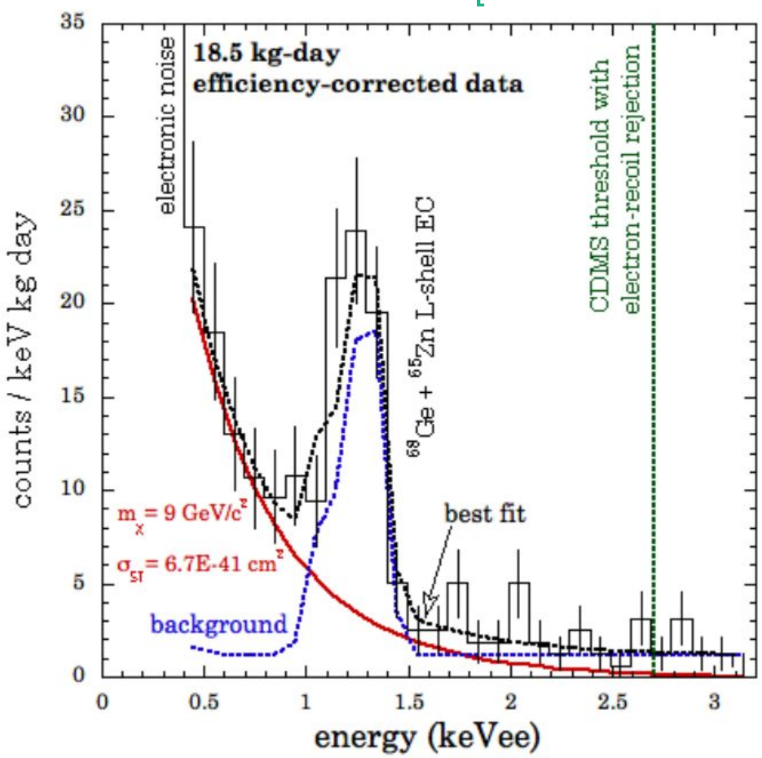
(Fig. from P. Gondolo)



CoGeNT "irreducible excess" Light WIMP or just background?

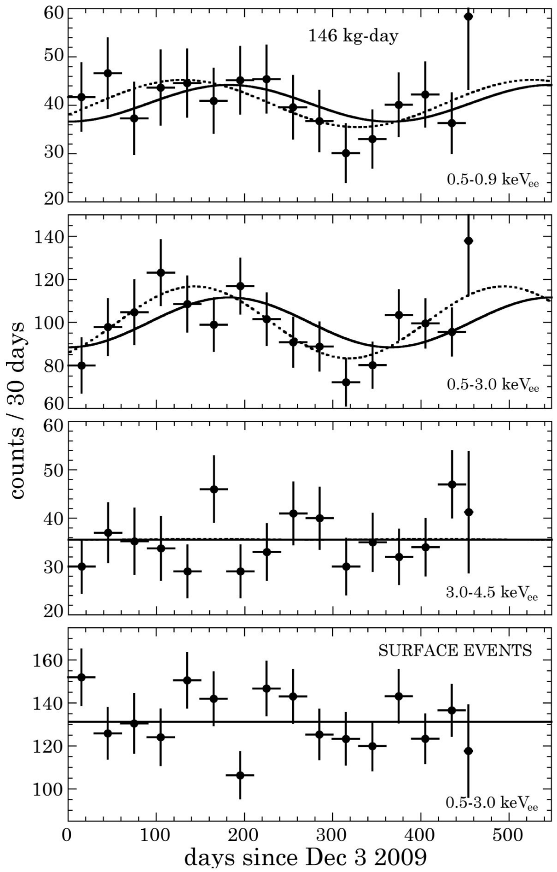
440g Ge detector in the Soudan Mine, Minnesota, with extremely low threshold, 0.4 keVee, 56 days of data, has excess "compatible" with light WIMP signal

Feb. 2010: Aalseth et al. [CoGeNT collaboration], arXiv:1002.4703 [astro-ph.CO]



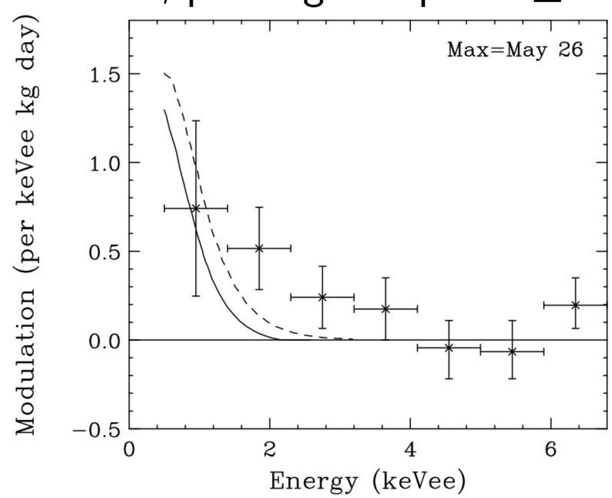
WIMP region only if exponential background is "constrained" (Kopp, Schwetz, Zupan addition to 0912.4264; Fitzpatrick, Hooper, Zurek 1003.0014; Chang, Liu, Pierce, Weiner, Yavin 1004.0697; Hooper, Collar, Hall, McKinsey 1007.1005; Kelso Hooper 1011.3076; ... the CoGeNT paper has about 650 citations)

CoGeNT annual modulation



June 2011: Aalseth et al. [CoGeNT coll.], arXiv:1106.0650 [astro-ph.CO]- 84 citations

15 months: events in the CoGeNT "irreducible excess" have a 16.6±3.8 annual modulation with a phase compatible with DAMA's, peaking at April 16±12 days

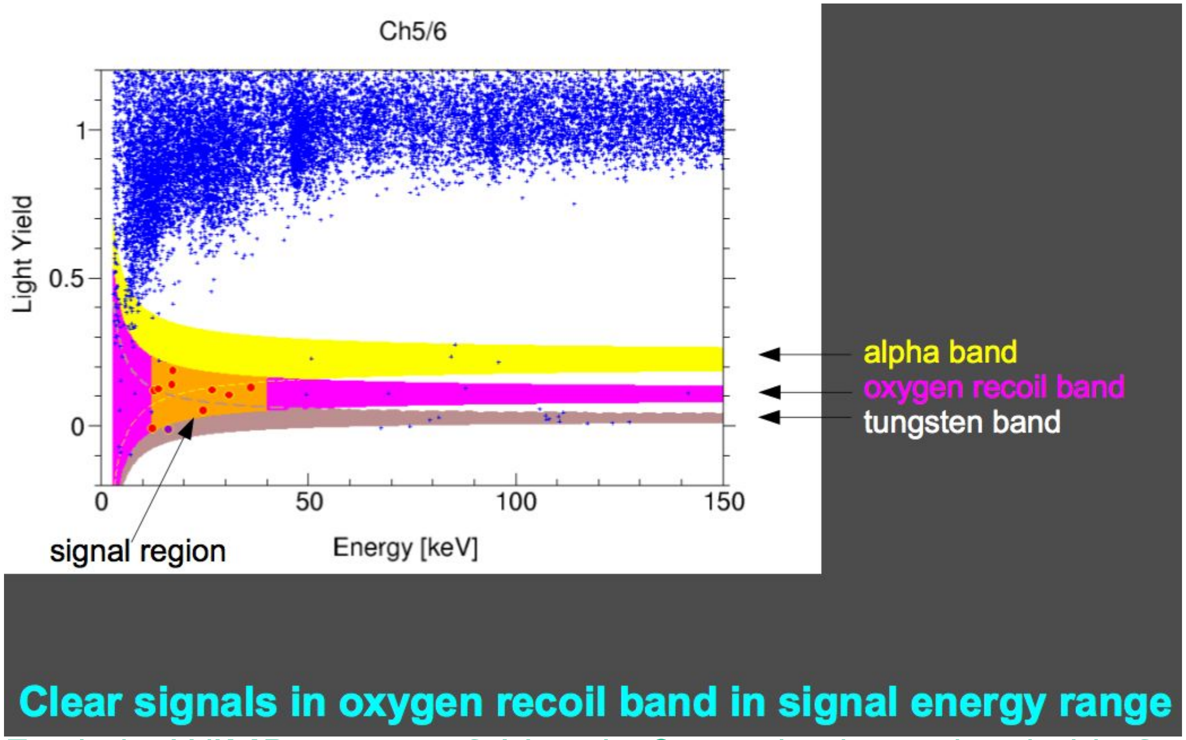


Kelso,Hooper; 1106.1066 [hep-ph]

Sept. 2011: CoGeNT background revised down (TAUP 2011 and 1208.5737)

CRESST II irreducible excess with 564 kgd $CaWO_4$ (Gran Sasso)

Feb 2010 Preliminary results,W.Seidel in WONDER, LNGS; Nov. F.Probst in Princeton



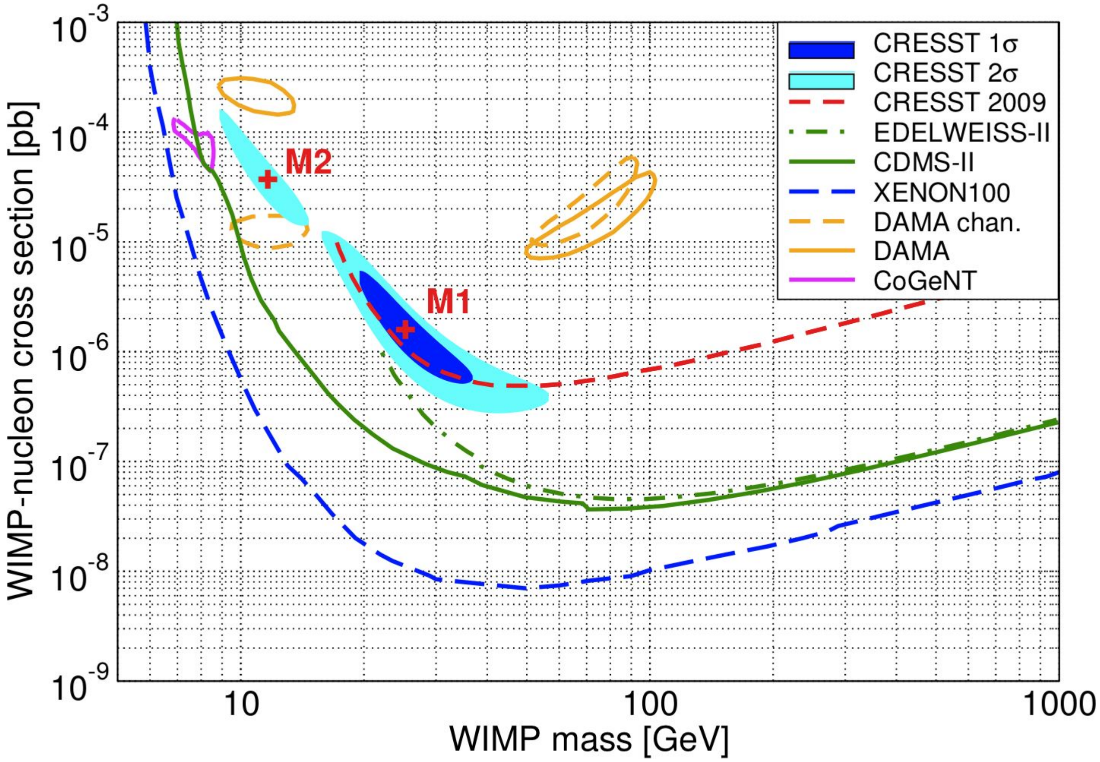
Excess of events in O band: point towards Light WIMPs!

For light WIMPs m< 10 GeV, only O recoils above threshold, Ca recoils for m$\simeq$ 10 GeV and W dominates for large m

CRESST II irreducible background

730 kg d; fit of background and WIMP signal together (best fit back. depends on signal)

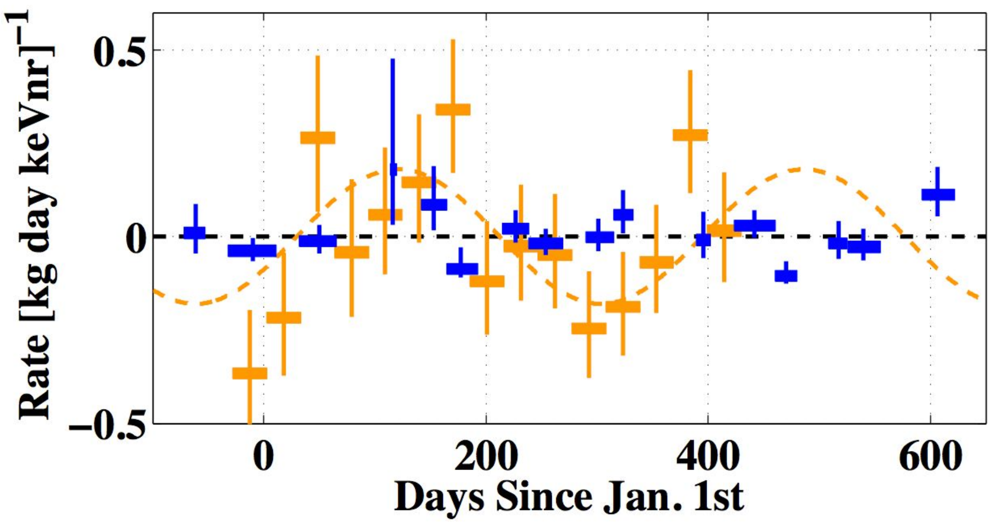
Sept. 2011, confirmed excess Angloher et al. 1109.0702



Negative Search:

CDMS negative annual modulation search March 2012: 1203.1309

CDMS (Ge): no modulation > 0.06 ev./keVnr kg day in 5 to 11.9 keVnr (CoGeNT thres. 0.4 keVee $\simeq$ 1.6 keVnr) to 99%CL.

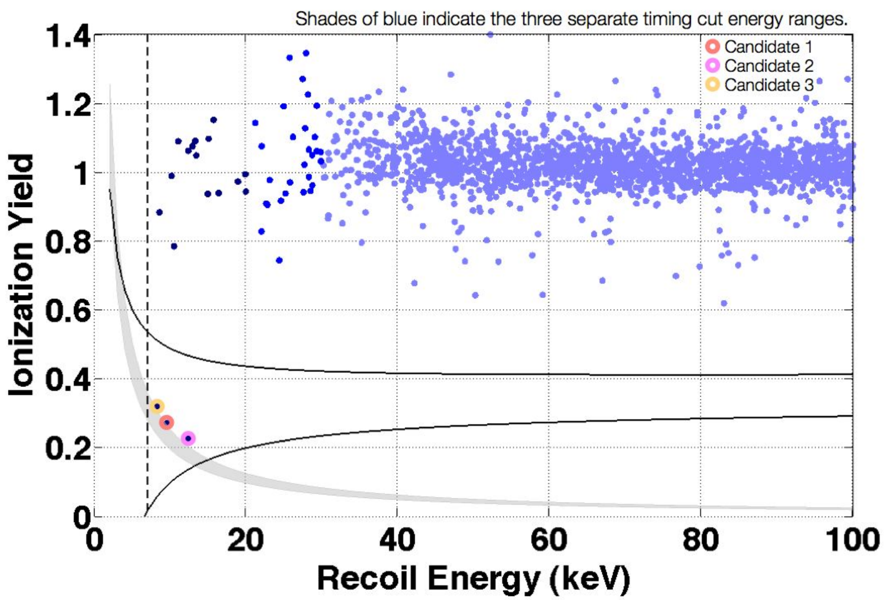


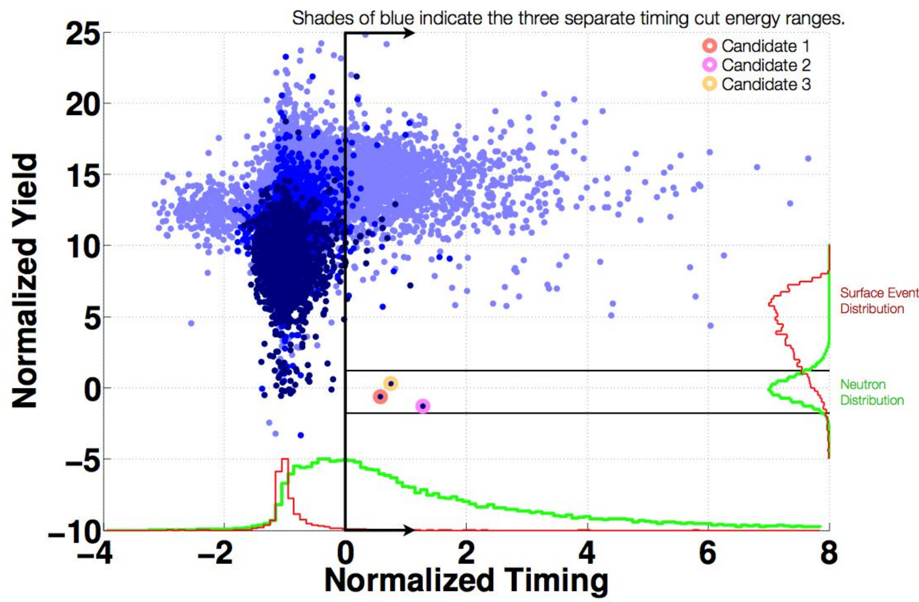
CoGeNT rate (orange)
CDMS rate (blue)

CDMS II 1203.1309

CDMS three candidate events in Si (April14, 2013)

140.23 kg-day from July 2007 to Sep. 2008 in 8 Si detectors, expected background events < 0.7 $(0.41^{+0.20+0.28}_{-0.08-0.24})$, 5.4% probability of being known backgrounds





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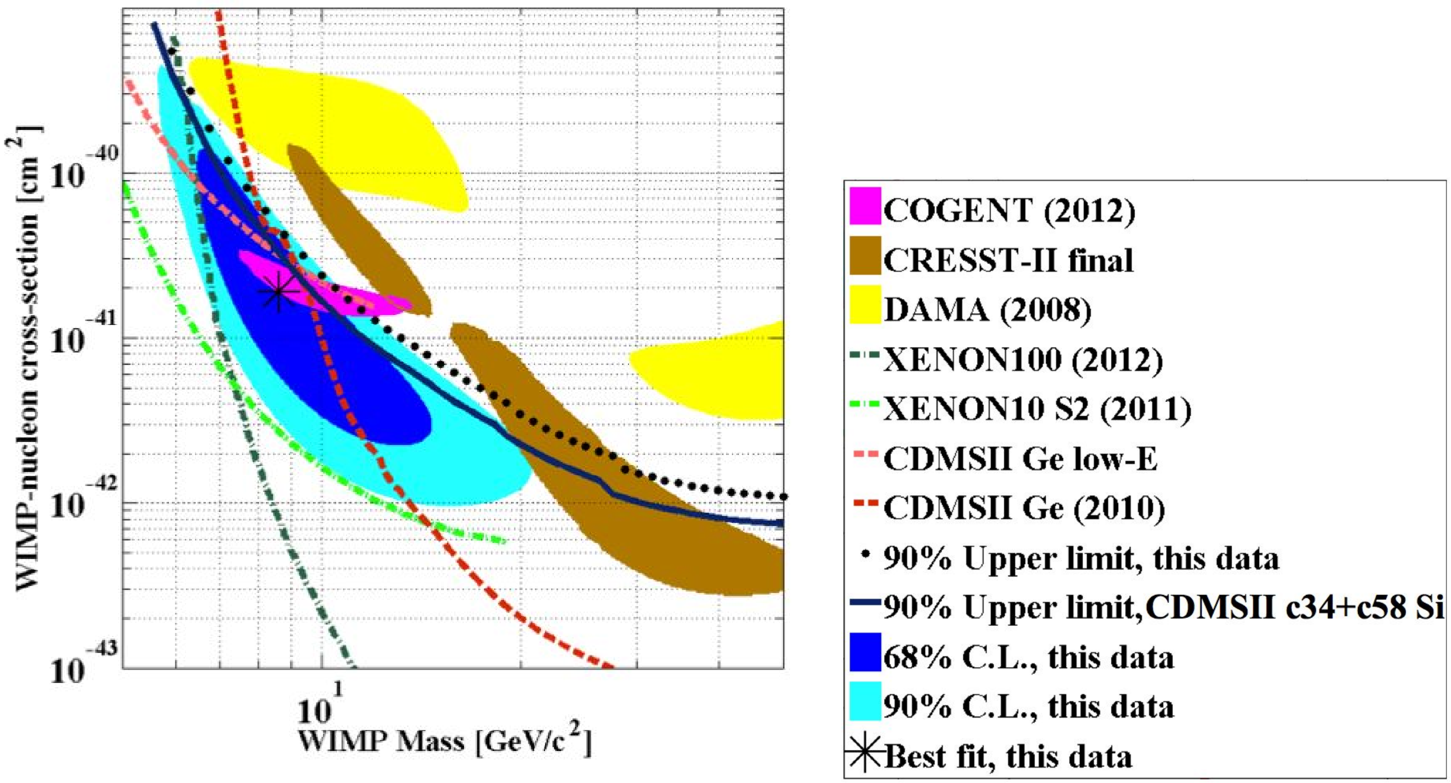
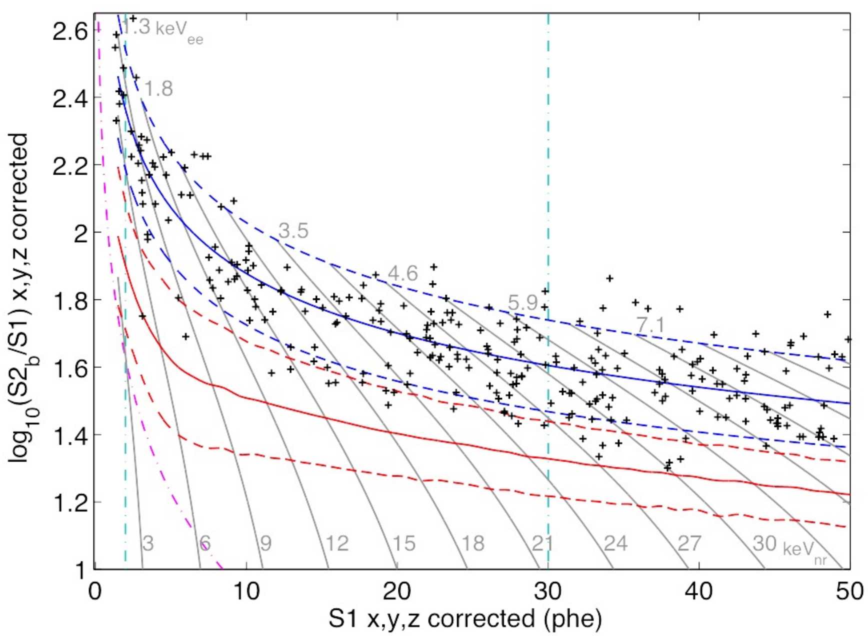
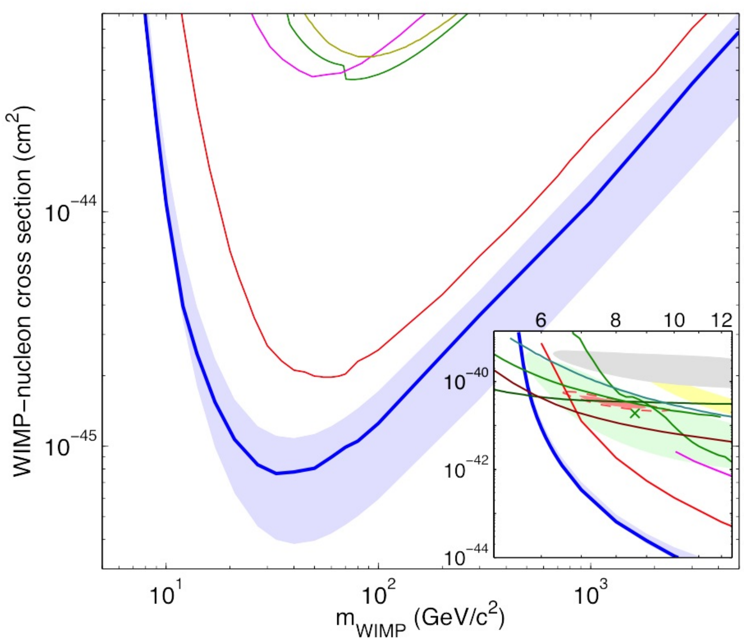


Most restrictive limits at present:

First LUX limits (Nov. 2013, 1310.8214)

Fiducial 118 kg of Xe- 85.3 days from April to Aug. 2013 (Sanford URF, South Dakota)

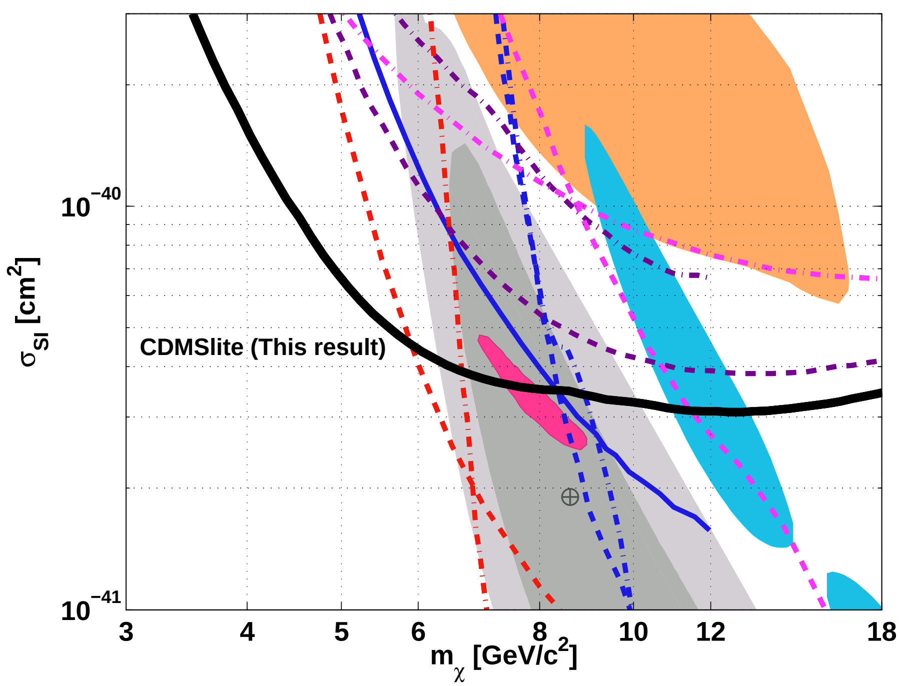




Most restrictive limits at present:

CDMSlite (Sept. 2013, 1309.3259- Fig from Dec. 2013)

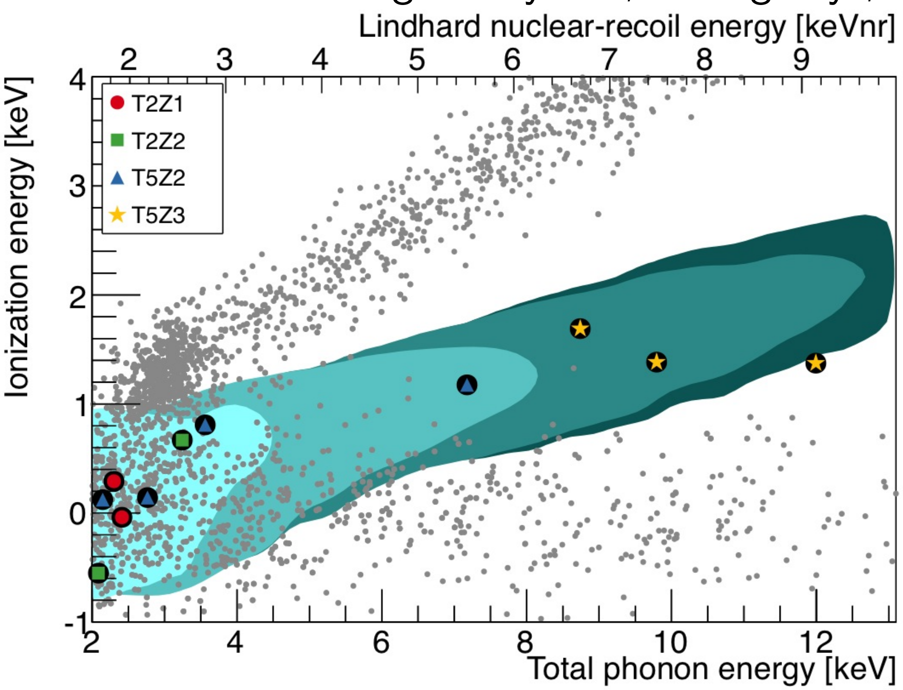
0.6 kg of Ge- 10 days- part of SuperCDMS- very low threshold: 0.170 keVee (Soudan Mine)

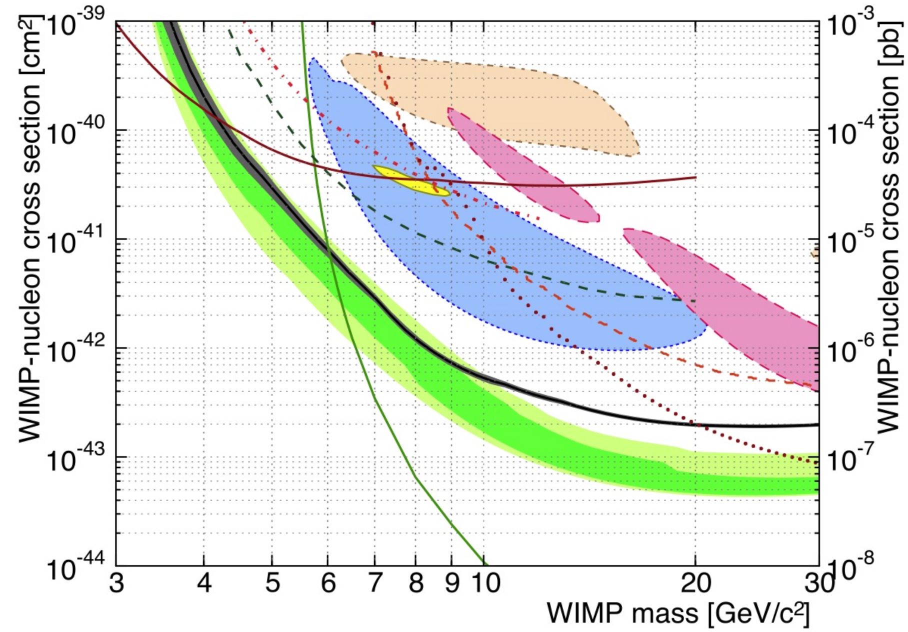


Most restrictive limits at present:

Super-CDMS (Feb. 2014, 1402.7137)

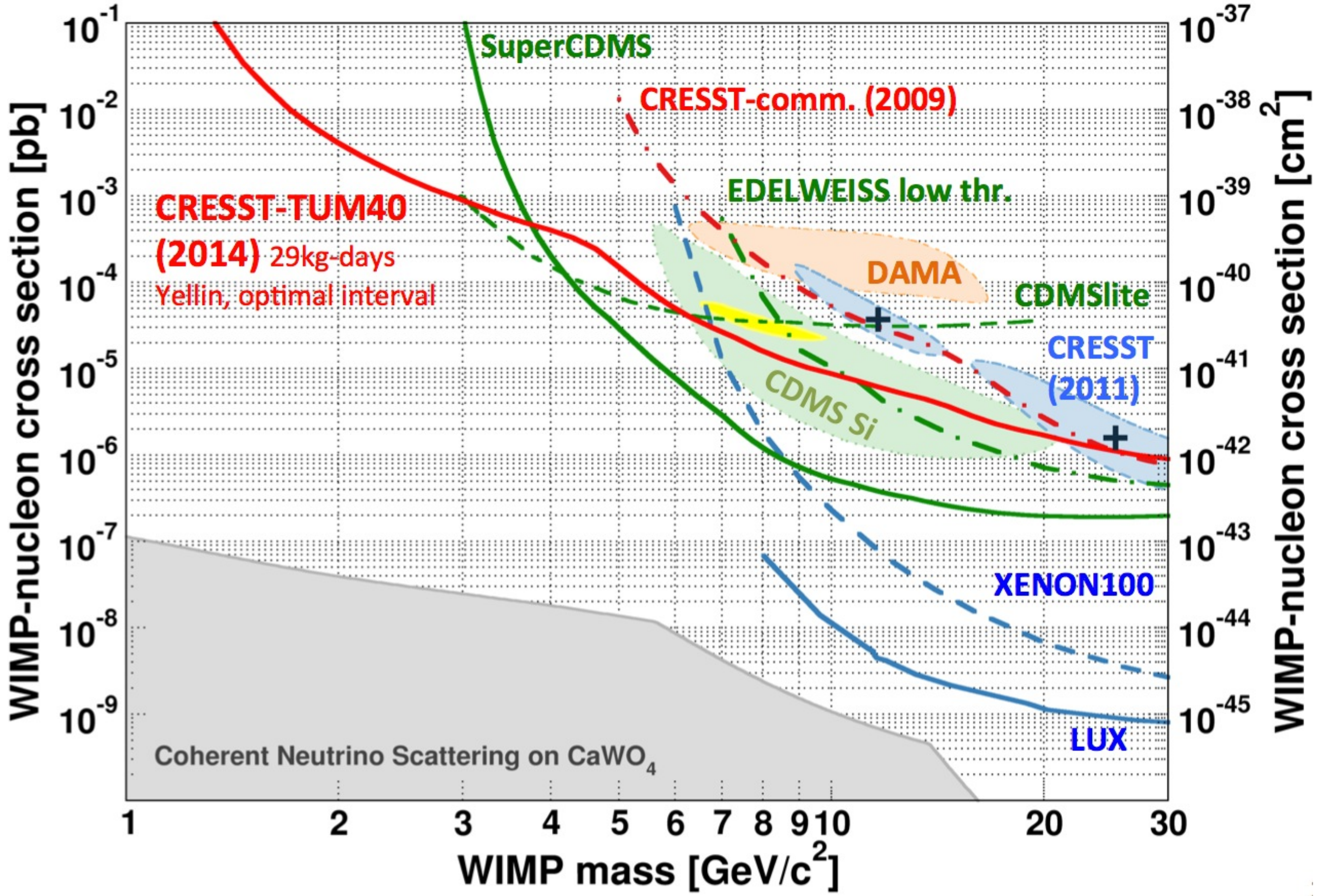
use 7 of 15 0.6kg Ge crystals, 577 kg-days, with threshold $\simeq 10$ keV (Soudan Mine, Minnesota)





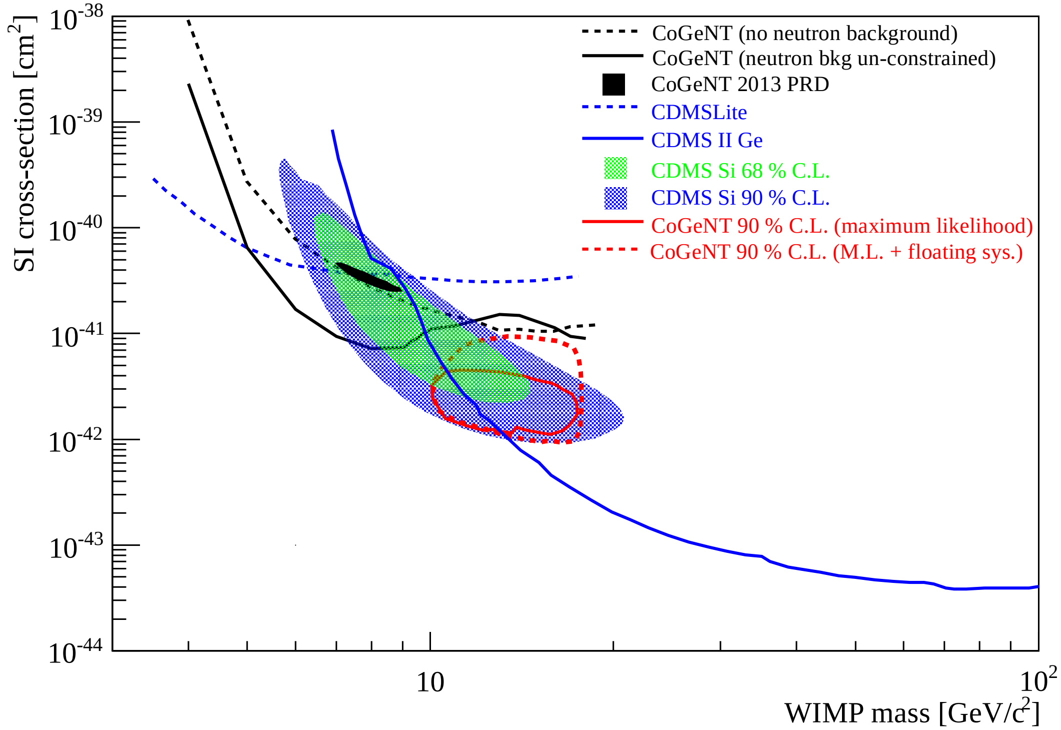
New CRESST-III results killed their own 2011 region

July 2014, 1407.3146



Weaker CoGeNT modulation 1401.3295 440g Ge detector with extremely low threshold, 0.4 keVee,- 3.4 y since 12-3-09 (Soudan Mine-Minnesota)

CoGeNT collaboration new data analysis 1401.6234



Only CDMS limits shown (in blue)

Maximum Likelihood Signal Extraction Method Applied to 3.4 years of CoGeNT Data

C.E. Aalseth,[1] P.S. Barbeau,[2,*] J. Colaresi,[3] J.I. Collar,[2] J. Diaz Leon,[4] J.E. Fast,[1] N.E. Fields,[2] T.W. Hossbach,[1] A. Knecht,[4,†] M.S. Kos,[1,‡] M.G. Marino,[4,§] H.S. Miley,[1] M.L. Miller,[4,¶] J.L. Orrell,[1] and K.M. Yocum[3]
(CoGeNT Collaboration)

arXiv:1401.6234v1 24 Jan 2014

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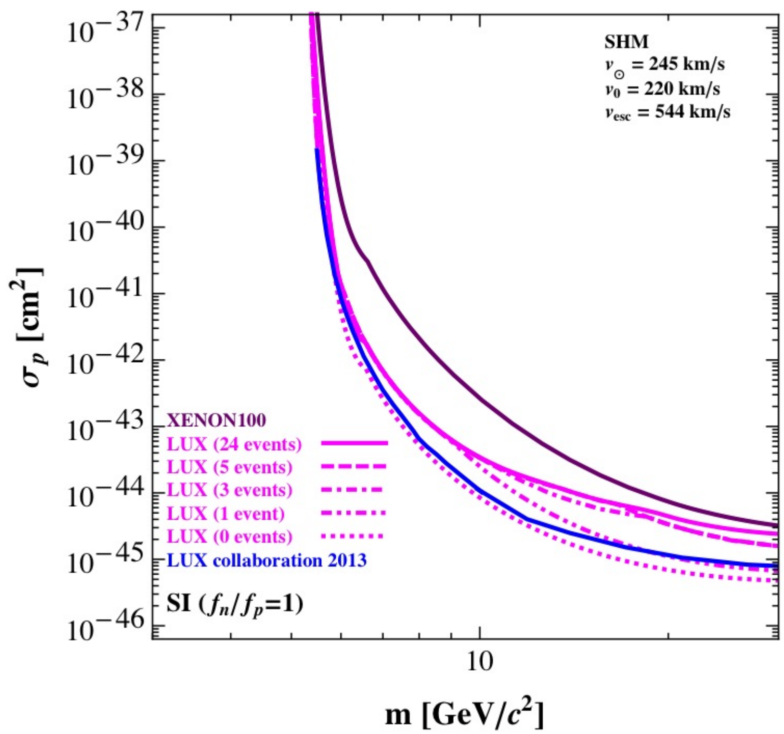
arXiv:1401.6234v2 27 Jan 2014

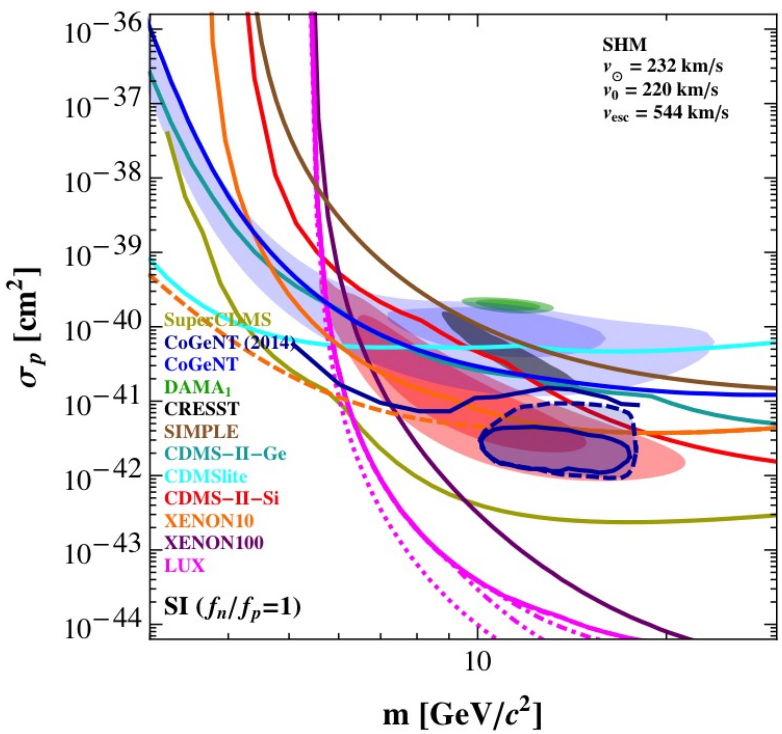
Matthew Bellis, Chris Kelso, Juan Collar and Nicole Fields independent analysis (IDM2014): “the fit gets worse when including WIMP component either as a Standard Halo or SGR like stream”- not posted yet but...

CoGeNT made public its dataset and analysis done independently by J. Davis, C. McCabe and C. Boehm, 1405.0495: “preference for light dark matter in CoGeNT recoils at less than 1σ”

My collaborators and I had found the same, using the old CoGeNT data analysis with new data

SHM data comparison for SI $f_n/f_p = 1$ Del Nobile, Gelmini, Gondolo, Huh 1311.4247



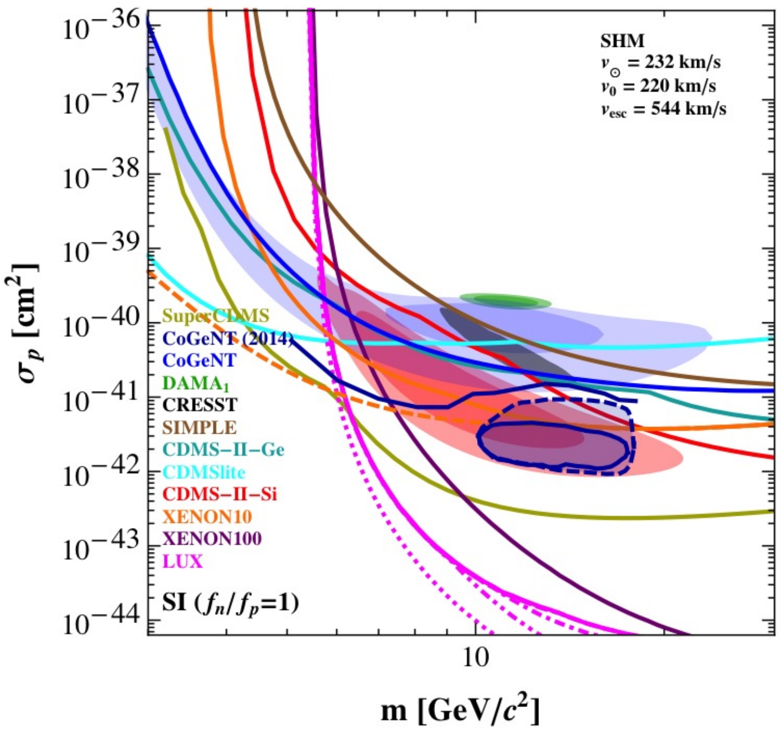


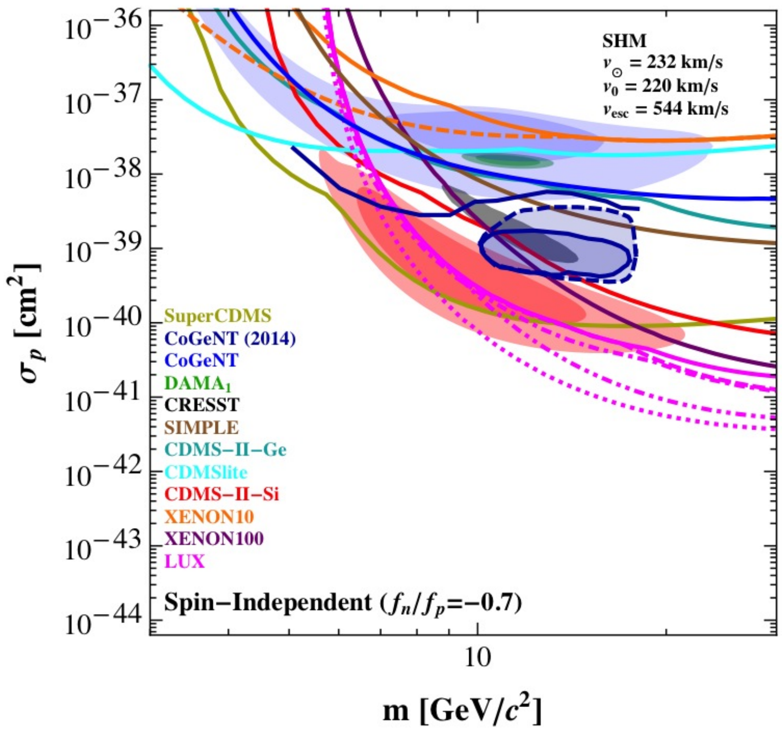
All regions rejected by a combination of LUX and CDMSlite bound? This is for elastic collisions and Spin Independent WIMP nucleus coupling with equal coupling to neutron and proton $f_n = f_p$ and assuming the Standard Halo Model

But large uncertainties in regions and bounds due to

- Detector response model: e.g. energy resolution, efficiency, fraction of energy deposited which is detectable, have large uncertainties at low E. Some of the bounds at low energy may be less restrictive?
- Type of DM interaction: contact spin-indep. or dep.? With different couplings with p and n (i.e isospin violating-IV)? Magnetic moment interaction (MDM)? Milli-charged DM? anapole DM? resonant DM? Form factor DM? inelastic endothermic (iDM)? inelastic exothermic (ieDM)?
- Uncertainties in the Dark Halo model: anisotropies, DM clumps and streams, "debris flows", velocity tails, "dark disk", escape speed: make a "Halo Independent data comparison" (tomorrow)
- Backgrounds: part, or all of the "DM signals" may be actually due to backgrounds? (tomorrow)

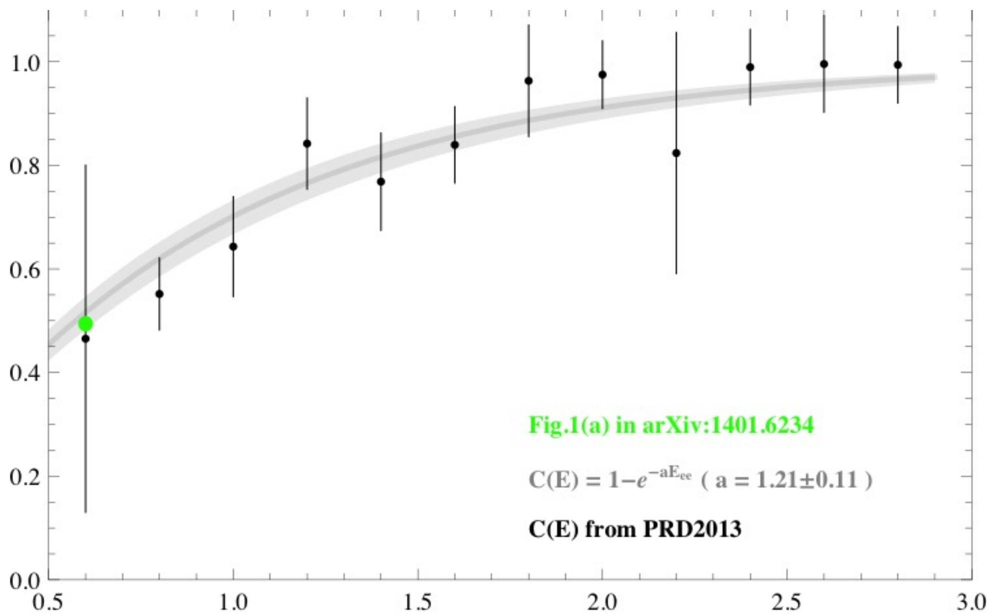
SHM data comparison for SI IC vs IV Del Nobile, Gelmini, Gondolo, Huh 1311.4247





With Isospin Violating $f_n/f_p = -0.7$ (Xe maximally suppressed) SI LUX 90%CL limit rejects CoGeNT and DAMA regions but not CDMS-Si. The Super-CDMS limit is very important.

CoGeNT 2014- our analysis Same analysis as for the older data, using the 2013 Surface Correction Factor C(E), after a time-rise cut



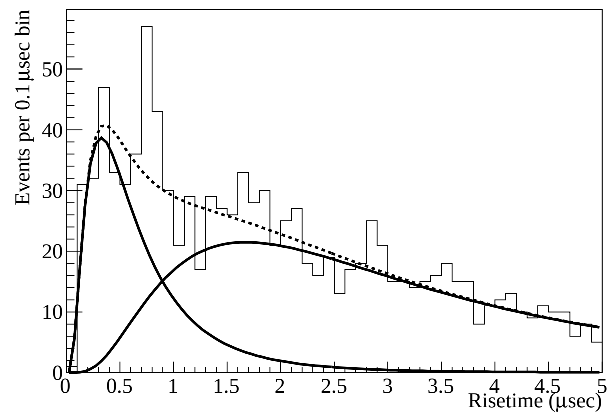
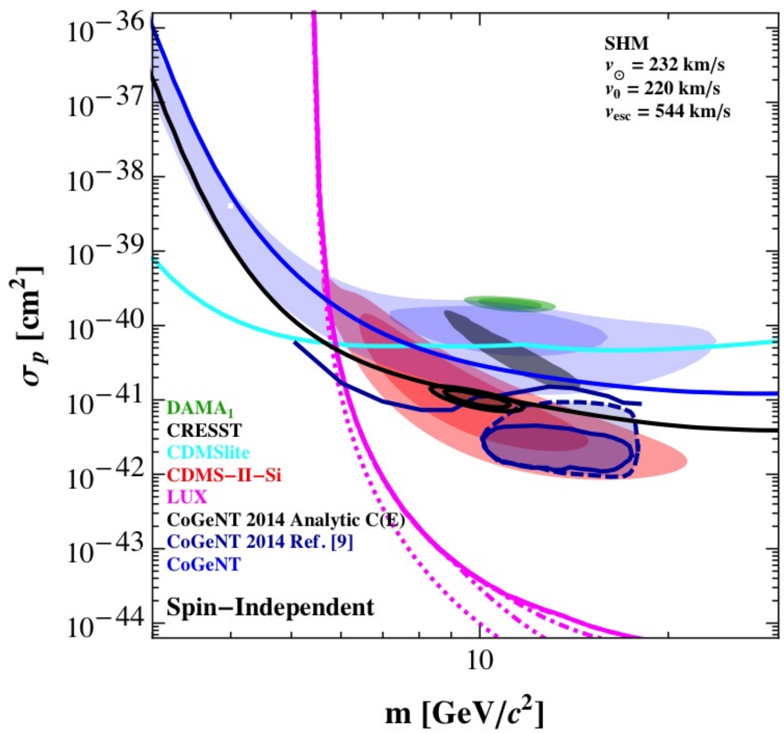
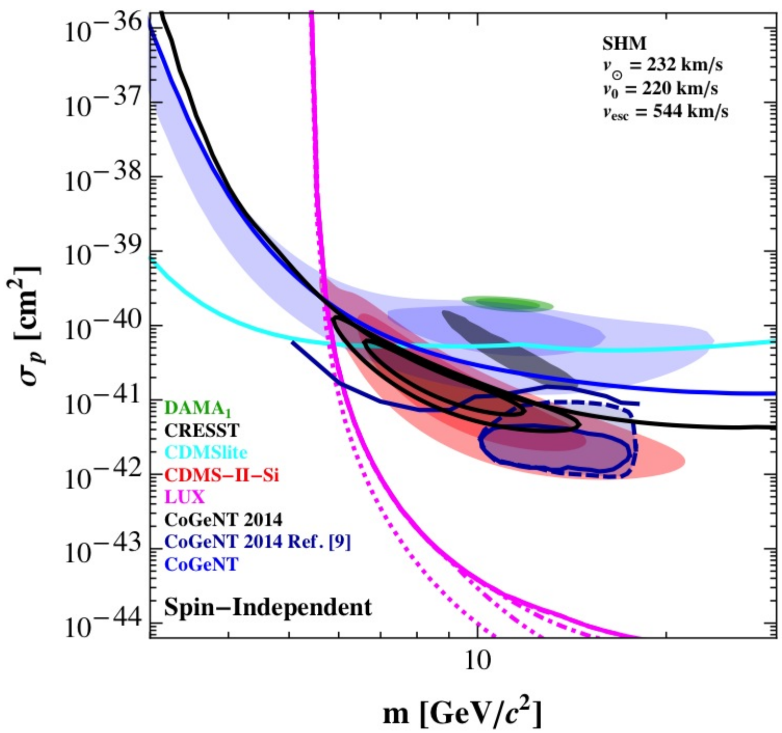


Fig.1 of arXiv:1401.6234

Standard Halo Model data comparison for SI IC Our CoGeNT 2014 rate regions Del Nobile, Gelmini, Gondolo, Huh 1401.4508)



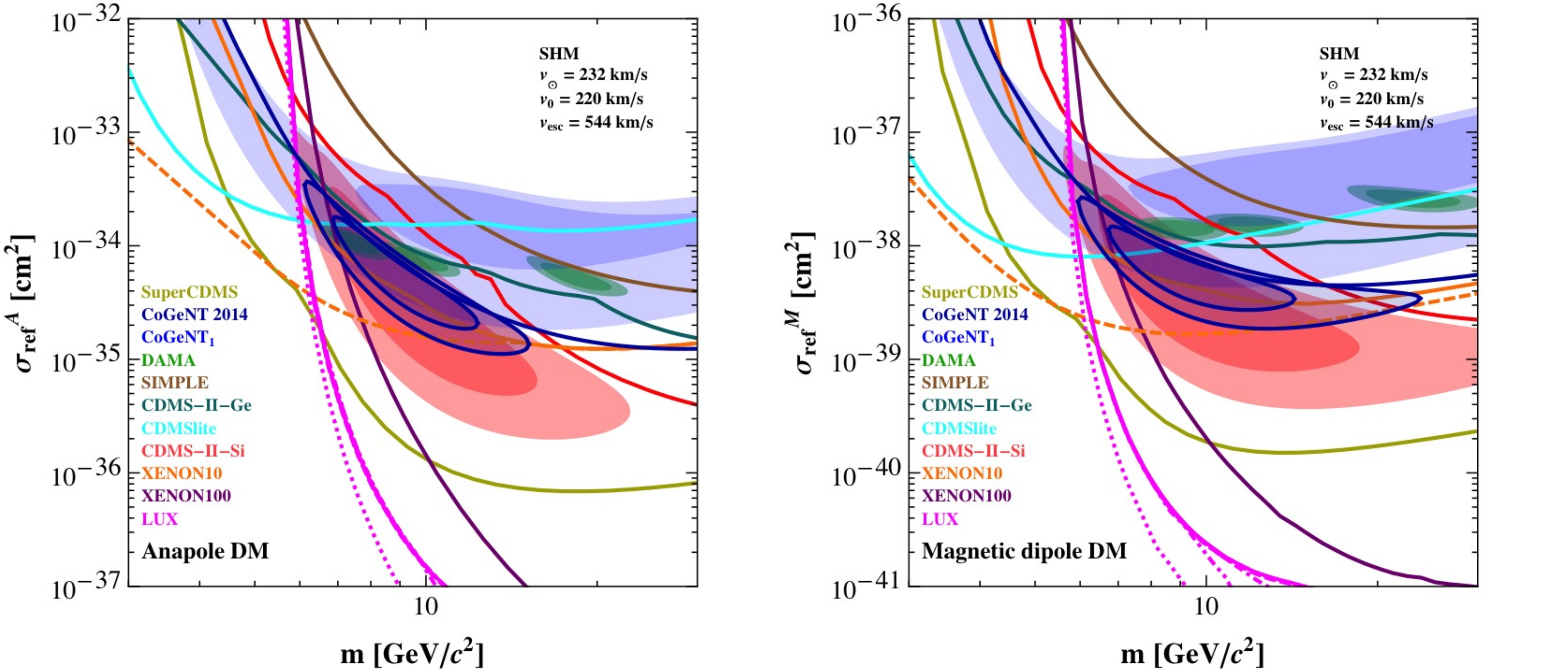
Using analytic fit curve to C(E)



Using C(E) data points (adopted in the rest)

SHM data comparison- Anapole and Magnetic Dipole DM

Del Nobile, Gelmini, Gondolo, Huh 1401.4508



DAMA, CoGeNT and CDMS-SI overlap! A small corner allowed was by XENON100, but is now rejected by LUX, CDMSLite and SuperCDMS

After considering many models, let us see which could work

For DAMA: Spin-Dependent coupling mostly to p

Recall - Na, I, F (DAMA, KIMS , COUPP, PICASSO, SIMPLE) have unpaired p,

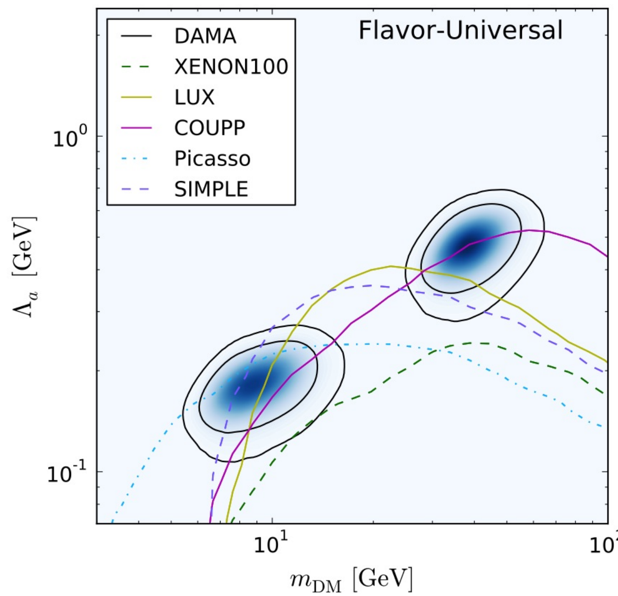
- Xe, Ge (LUX, XENON, CDMS, CoGeNT) have unpaired n

Pseudoscalar coupling (Arina, Del Nobile, Panci, 1406.5542)

$$L_{eff} = \frac{1}{2\Lambda_a^2} \sum_{N=p,n} g_N \, \bar{\chi}\gamma^5\chi \, \bar{N}\gamma^5 N$$

leads to $(\overrightarrow{S_\chi} \cdot \vec{q})(\overrightarrow{S_N} \cdot \vec{q})$ non relativistic coupling

Figure for $g_p/g_n = -16.4$



Only DAMA region shown- Bayesian analysis, marginalizing over experimental systematics and astrophysical uncertainties (regions and limits correspond to different halo models!) - Potential problem with indirect detection via neutrinos from the Sun

For DAMA: Magnetic of Spin-Dependent Inelastic DM

In iDM in addition to the DM state χ with mass m_χ there is an excited state χ^* with mass m_{χ^*}

$$m_{\chi^*} - m_\chi = \delta$$

and inelastic scattering $\chi + N \to \chi^* + N$ dominates over elastic. Thus

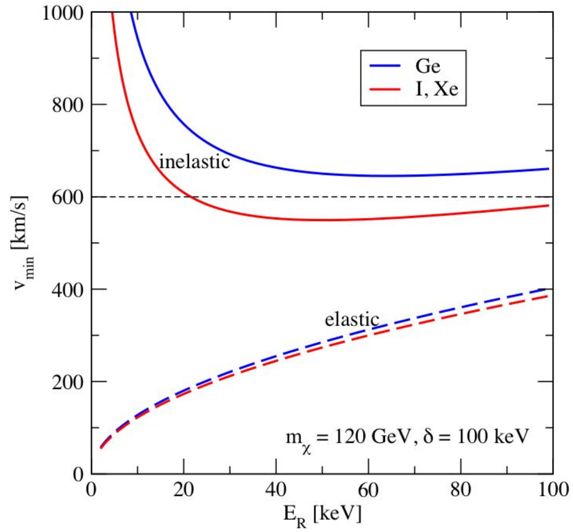
$$v_{min}^{inel} = \left| \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}} \right|$$ instead of $v_{min}^{el} = \sqrt{\frac{ME_R}{2\mu^2}}$

Inelastic Endothermic DM (iDM) i.e. Inelastic with $\delta > 0$%This was the initial idea.

Favors heavy materials (I in DAMA over Ge in CDMS and F in SIMPLE, Picasso and COUPP) and enhances the annual modulation amplitude Tucker-Smith, Weiner 01 and 04; Chang, Kribs, Tucker-Smith, Weiner 08; March-Russel, McCabe, McCullough 08; Cui, Morrisey, Poland, Randall 09, many more.

. .

Inelastic DM (IDM)(fig from T. Schwetz)



$$v_{min}^{inel} = \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}}$$

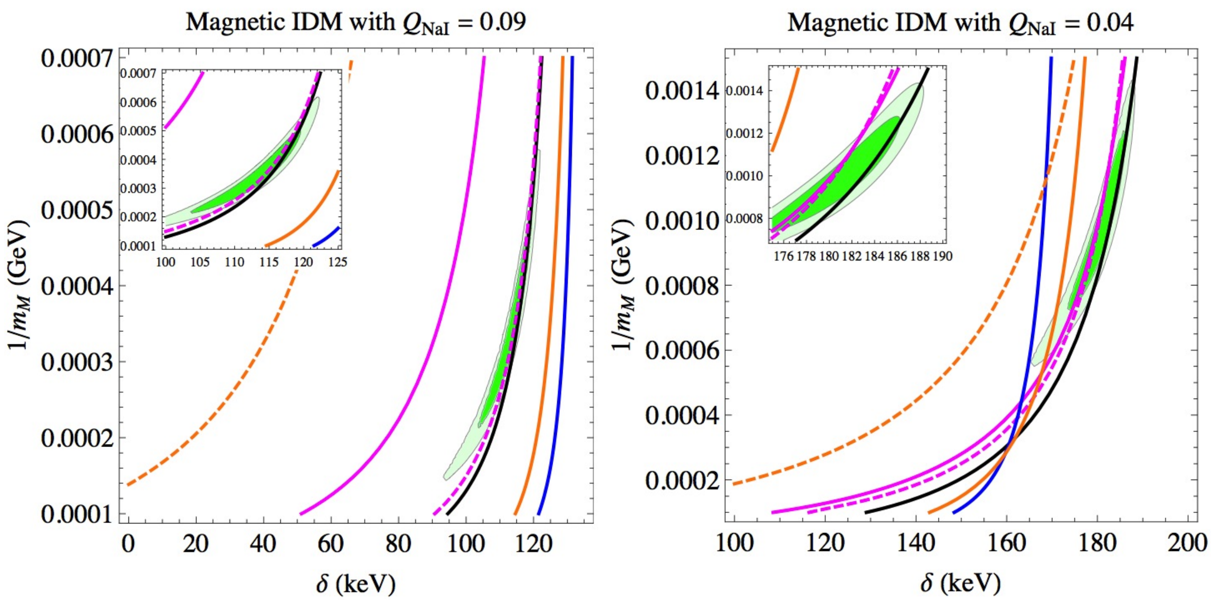
$$v_{min}^{el} = \sqrt{\frac{ME_R}{2\mu^2}}$$

Only high v DM particles have enough energy to up-scatter, and v_{min}^{inel} decreases with increasing target mass M, thus targets with large M are favored (better I than Ge or F...).

This was OK for DAMA vs CDMS- But Xe is heavier and rejects SI-iDM- But iDM could still work for Magnetic coupling (MiDM) -I has a large nuclear magnetic moment- if Q_I in NaI is small Chang, Weiner, Yavin 1007.4200, Barello, Chang, Newby 1409.0536 or DM with Spin-Dependent coupling to only protons. However KIMS (CsI) bounds cannot be weakened much (same element I) Barello, Chang, Newby 1409.0536

SHM data comparison- Magnetic Inelastic DM (MiDM)

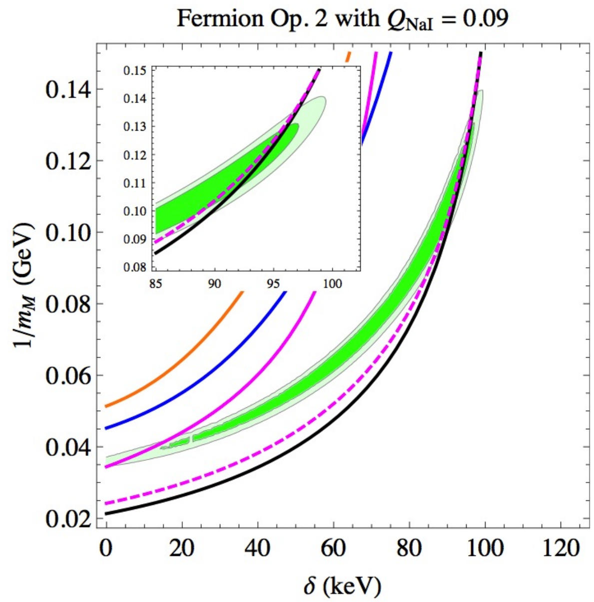
Here $1/m_M = e\mu_\chi$. For Q_I =0.09 $m = \chi = 58.0$ GeV and for Q_I =0.04 $m = \chi = 122.7$ GeV (best fit values) Barello, Chang, Newby 1409.0536



Best limits LUX (blue), Xenon100 (solid orange), KIMS (magenta, solid $Q_I = 0.05$ and dashed 0.10), COUPP (black). DAMA might be compatible only for low values of Q_I in NaI, because δ required is larger. They assume Q_I can be different in NaI and in CsI.

SHM data comparison- Inelastic DM with Spin coupling to p

Here just one operator $\sim \overrightarrow{S_N} \cdot \vec{q}$ (but no complete model!), dimensionful coupling is $1/m_M^2$ (m_M is mediator mass) and $m = \chi = 44.2$ GeV (best fit value)



Best limits LUX (blue), Xenon100 (solid orange), KIMS (magenta, solid $Q_I = 0.05$ and dashed 0.10), COUPP (black). But Cs in KIMS not included (lack of form factor), has also unpaired p and would make bounds stronger.

After considering many models, let us see which could work

For CDMS-Si: Inelastic Exothermic (ieDM)

In iDM in addition to the DM state χ with mass m_χ there is an excited state χ^* with mass m_{χ^*}

$$m_{\chi^*} - m_\chi = \delta$$

and inelastic scattering $\chi + N \to \chi^* + N$ dominates over elastic. Thus

$$v_{min}^{inel} = \left| \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}} \right|$$ instead of $v_{min}^{el} = \sqrt{\frac{ME_R}{2\mu^2}}$

Inelastic Endothermic DM (iDM) i.e. Inelastic with $\delta > 0$ was the initial idea.

Tucker-Smith, Weiner 01 and 04; Chang, Kribs, Tucker-Smith, Weiner 08; March-Russel, McCabe, McCullough 08; Cui, Morrisey, Poland, Randall 09, many more. . .

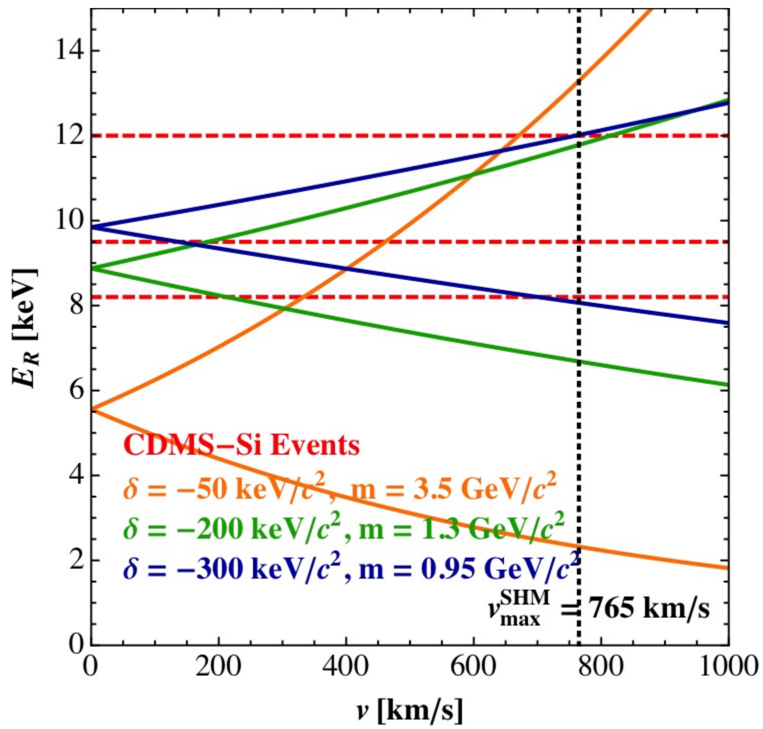
Inelastic Exothermic DM (ieDM) i.e. Inelastic with $\delta < 0$

Favors light materials (Si in CDMS over Xe in LUX and XENON) and reduces the annual modulation amplitude Graham, Harnik, Rajendran, Saraswat 1004.0937

Problem: make the excited state sufficiently long lived to be still present!

Inelastic Exothermic Scattering

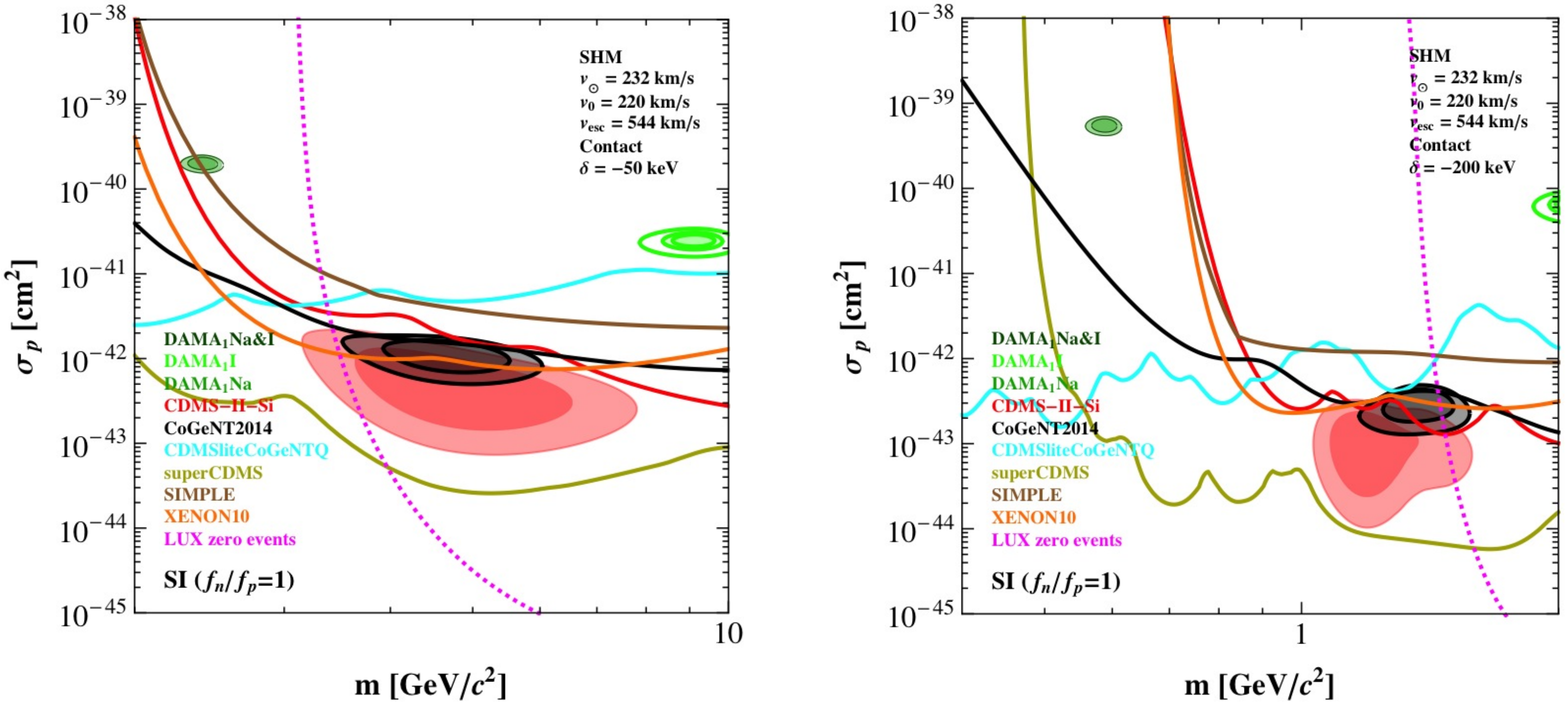
GG, Georgescu, Huh 1404.7484



Characteristic recoil energy is $E_\delta = \mu_\chi \delta / M \simeq m_\chi \delta / M$ for $m_\chi << m_T$, which is larger for smaller M (for larger M it may be below threshold).

SHM data comparison- Inelastic Exothermic (ieDM)

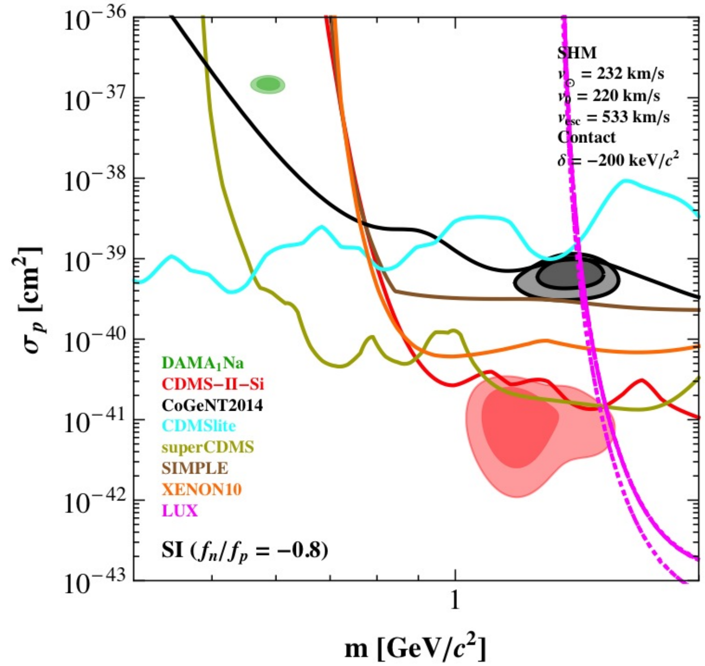
GG, Georgescu, Huh 1404.7484



Frandsen and Shoemaker 1401.0624 with only CDMS-Si, LUX and XENON10 found that with $\delta \simeq$-200 keV SI IC coupling, CDMS-Si AND CoGeNT regions were compatible with all limits (not DAMA). But Super-CDMS rejects this case Other couplings may work. For example...

Inelastic Exothermic SI "Ge-Phobic" DM

Gelmini, Georgescu, Huh 1404.7484



Exothermic $\delta = -200$ keV weakens Xe bounds, $f_n/f_p = -0.8$ weakens Ge bounds: CDMS-Si allowed by all bounds- but NOT CoGeNT or DAMA

Synopsis

Situation is confusing, many uncertainties and possibilities and data changing all the time.

By choosing kinematical and dynamical ways to suppress the best limits due to searches with negative results it might be still possible to find DM candidates which make either the DAMA/LIBRA region or the CDMS-Si region compatible with all bounds while assuming they are due to DM in Standard Halo Model, but not simultaneously compatible also with each other or with CoGeNT.

For DAMA: use the large p spin component of I and Na or the large magnetic moment of I to disfavor Xe and Ge (have unpaired$n$) upper limits. But this would still keep the F limits (SIMPLE, PICASSO, COUPP), since F also has unpaired p. So add endothermic inelasticity to disfavor light nuclei (like F and Ge) with respect to I

For CDMS-Si: use Isospin violation to disfavor SI coupling of Xe and Ge and exothermic inelasticity to disfavor nuclei heavier than Si (Xe and Ge again). The SI coupling disfavors light nuclei (F) because it is proportional to A^2.

Notice that this game assumes that Nature has chosen for the DM the candidates that make the best present upper limits from direct dark matter searches with negative results weaker in a weird coincidence! (is this believable?)

Are these conclusions are independent of the choice of halo model?